Atmospheric Dynamics I

1b. Determine the relationship of appropriate forces to the various types of winds.

Scale Analysis of Forces

- The equations that describe wind motions contains several forces, including:
  - Pressure gradient forces
  - Earth rotational forces
  - Curvature forces
  - Frictional forces

Scale Analysis of Forces

- The size of the wind system determines which forces are large and which are small.
- For Synoptic and Macro-scale systems, Coriolis force becomes important.
- For Micro and meso-scale systems, Coriolis force can be ignored.

Scale analysis of Forces

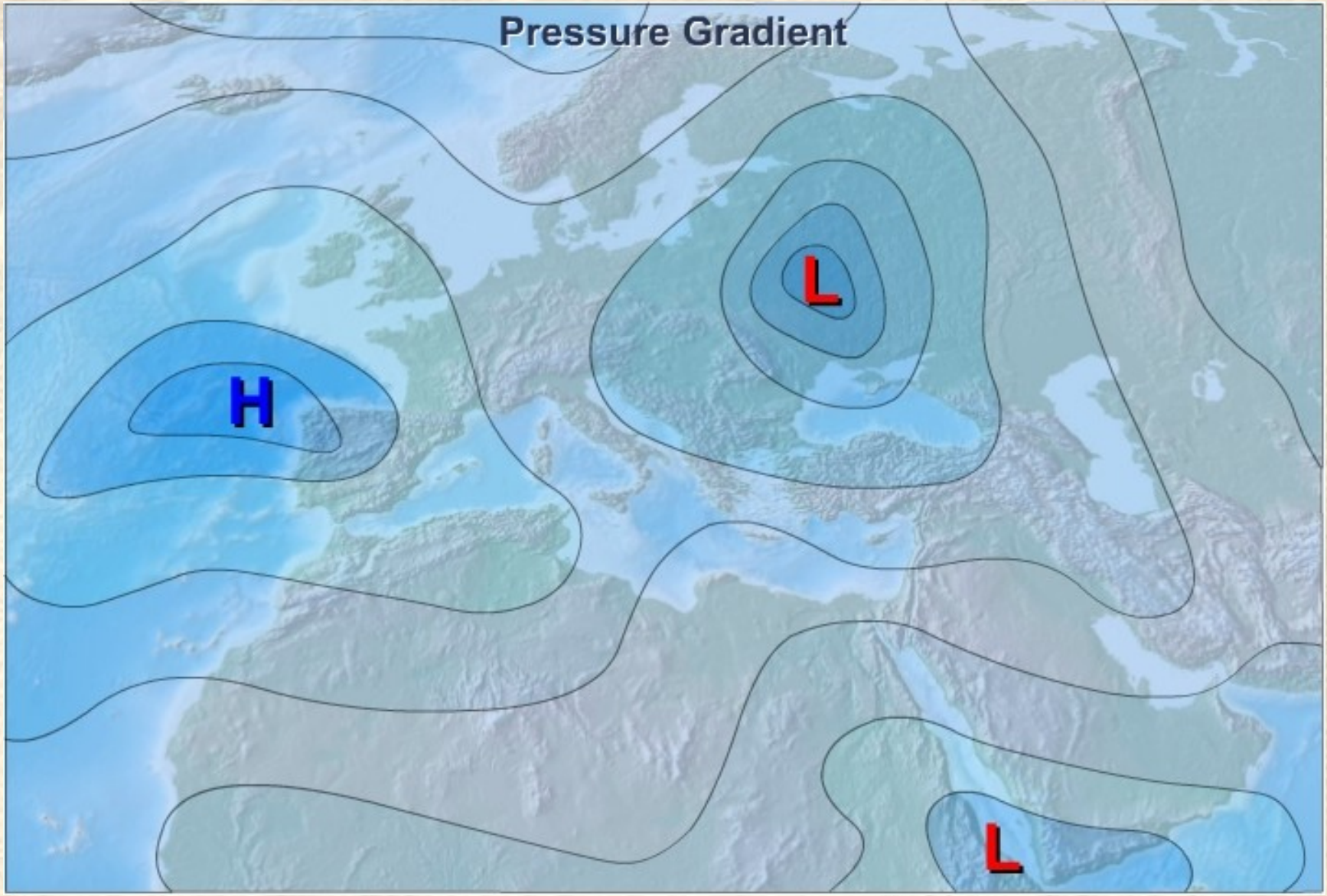
- Winds behave differently, depending on which forces are active.

- For winds blowing at elevations well above the ground, friction can be ignored. But friction is very important near the ground.

Gradient Forces

- Pressure Gradient Force (PGF) - A force acting on a parcel of air, resulting from the difference in pressure on either side of the parcel.

  – Pressure Gradient (PG):
    - Equation: PG = $\Delta P/\Delta n$ (A scalar: magnitude only)
    - Rate of pressure change (ΔP) with distance (Δn).
    - **Always** measured perpendicular to the isobars. (Along the "n" axis in the natural coordinate system)


Pressure Gradient
L
H
L

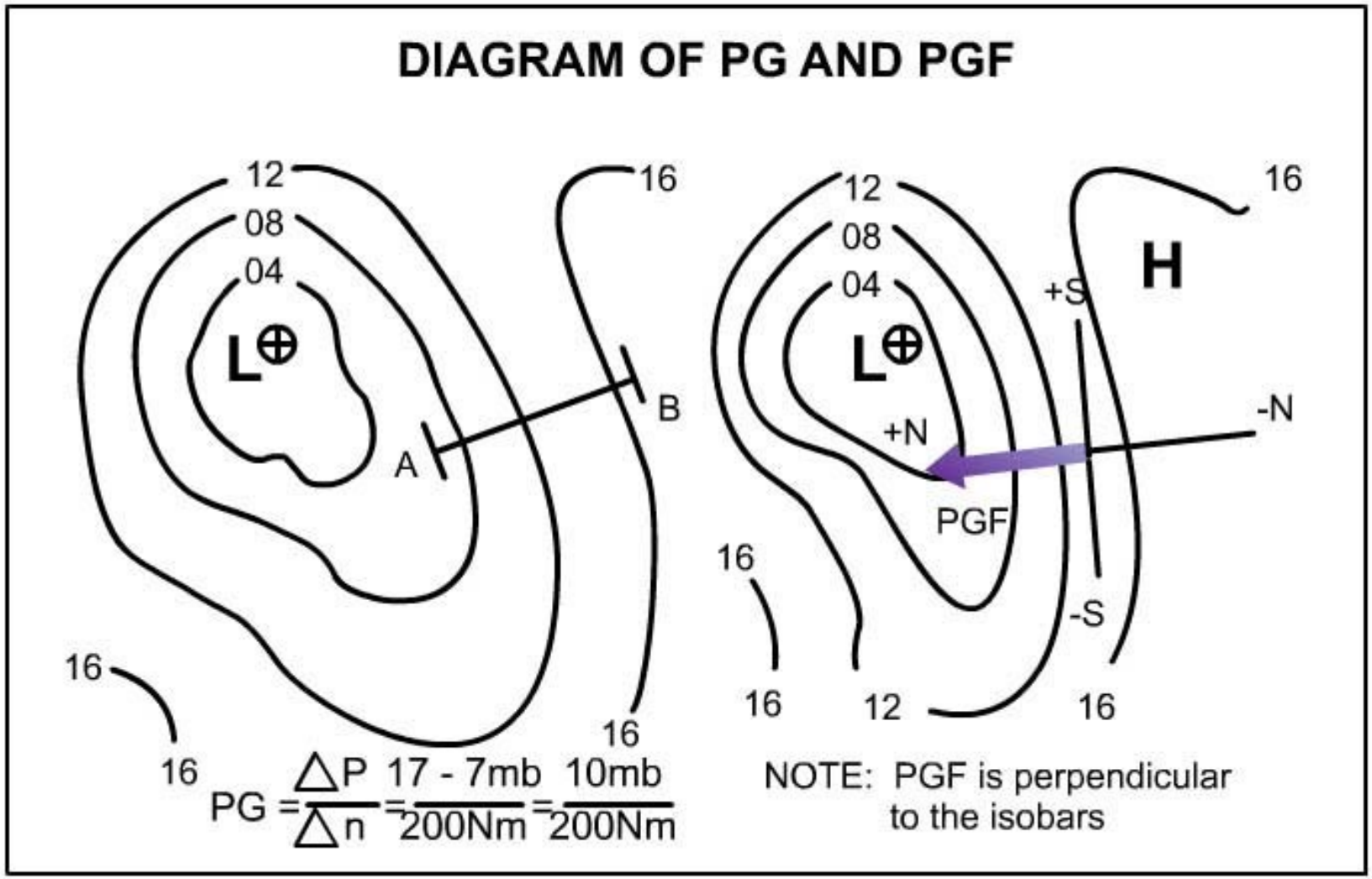


DIAGRAM OF PG AND PGF
12
08
04
L
16
A
B
16
16
16
PG = ΔP / Δn = 17 - 7mb / 200Nm = 10mb / 200Nm
12
08
04
L
H
+S
-S
+N
-N
PGF
16
16
12
16
16
NOTE: PGF is perpendicular to the isobars

Gradient Forces

- Changes in pressure result from a change in the quantity of mass over a given point. **$P = \rho g h$** This may be the result of the actual removal/addition of mass or a change in the density of the atmosphere by differential heating/cooling (P=prT).

Gradient Forces

- **PGF = $\frac{-1}{\rho} \frac{\Delta P}{\Delta n}$ directed along +Δn**

- The magnitude of PGF is directly proportional to the strength of PG. If ΔP/Δn increases, then PGF increases.

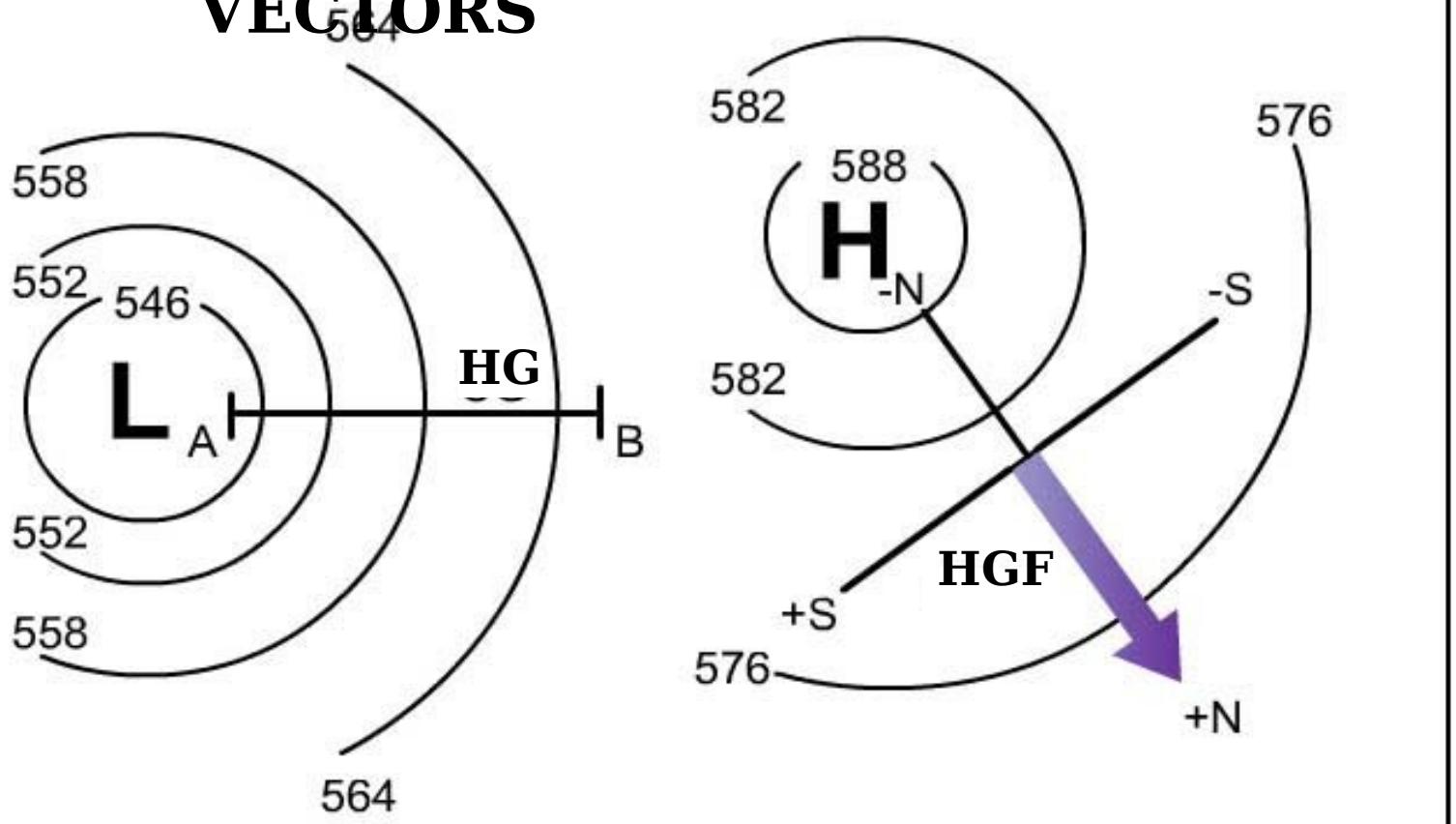
- This force will act to move air parcels towards lower pressures which initiates the wind.

Gradient Forces

- Height Gradient Force (HGF) The force that represents PGF on a constant pressure chart.

  - Height Gradient (HG):
    - Equation: HG = $\Delta z/\Delta$ n (A scalar: magnitude only)
    - The rate of height change (Δz) with distance (Δn) on a constant pressure surface.

HGF AND HG WITH VECTORS



Gradient Forces

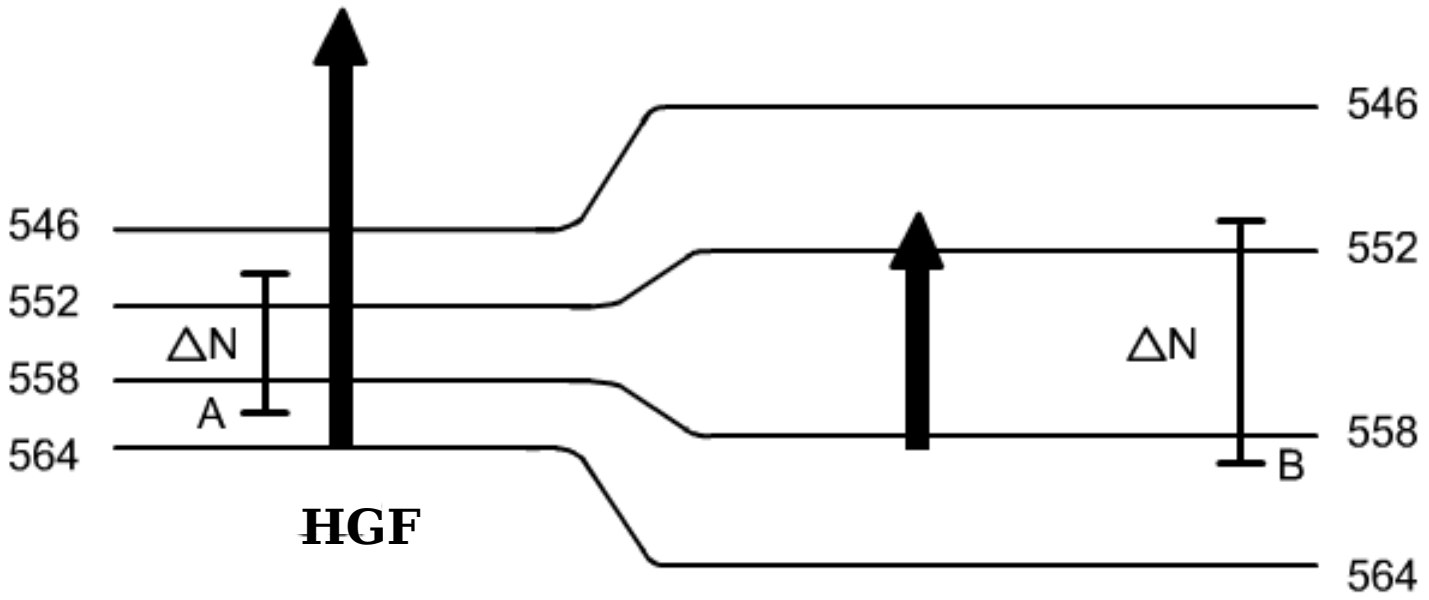
- Differences in virtual temperature and the quantity of mass over a given point in the atmosphere result in changes in thickness between layers. These variations in height result in the HG.

  – **HGF = -g** $\frac{\Delta z}{\Delta n}$ directed along the + Δ**n**

  – HGF is directly proportional to the strength of HG.

  If $-\frac{\Delta z}{\Delta n}$ increases, then HGF increases.

$$HGF = -\frac{\Delta z}{\Delta n} g$$



HGF WITH DIFFERENT HEIGHT GRADIENTS

Gradient Forces

- **HGF = -g $\Delta z / \Delta n$**

- This force will initiate the wind by causing air parcels to move toward lower heights which.

Calculate HG with basic units canceling . Then calculate direction of HGF

- **HGF = -g $\Delta z / \Delta n$**
- **Example:**

The Balance of Forces Governing the wind

- Several force may act on the moving air parcels to alter their behavior and path. Many types of “balanced” wind flows may evolve as different forces become equal and opposite to one another.

The Balance of Forces Governing the Wind Horizontal Momentum Equations

- Several types of wind flows are governed by forces in the following two horizontal momentum equations (in natural coordinates) (Holton, 1992):

$$\frac{\Delta V}{\Delta t} = -1\,\frac{\Delta P}{\rho\,\Delta s} \qquad (1)$$

(A) **(B)**

  - Term A: Wind Acceleration
  - Term B: PGF when the winds are not parallel to the isobars

Note: Equation 1 is active only when the wind flow is ***not parallel*** to the pressure (or height) contours.

The Balance of Forces Governing the Wind

$$\frac{V^2}{r} + fV = -\frac{1}{\rho}\frac{\Delta P}{\Delta n} \qquad (2)$$

(A) (B) (C)

- **Term A: Wind flow curvature influence**
- **Term B: Earth rotational influence**
- **Term C: PGF when the winds are parallel to the isobars.**

Note: Equation 2 is active only for winds blowing *parallel* to the pressure (or height) contours.

Wind Acceleration From the PGF and HGF *(Active Forces: PGF)*

- The PGF causes air to accelerate from higher pressure toward lower pressure.

- The HGF is identical to the PGF, except that the HGF is observed on isobaric maps (I.e., maps of constant pressure). The HGF vector always points in the direction of lower heights and is perpendicular to the height contours.

Wind Acceleration From the PGF and HGF

- Equation 1 describes the wind acceleration ($\Delta V/\Delta t$) due to the PGF (Term B) [see boxed items below]. Since the wind flow is not parallel to the isobars, Equation 2 is not a factor in describing this wind flow.

$$\frac{\Delta V}{\Delta t} = \frac{-1}{\rho}\frac{\Delta P}{\Delta s} \qquad (1)$$

(A) **(B)**

$$\frac{V^2}{r} + fV = \frac{-1}{\rho}\frac{\Delta P}{\Delta n} \qquad (2)$$

(A) **(B)** **(C)**

Wind Acceleration From the PGF and HGF

- The amount of the wind acceleration is directly proportional to the strength of the PGF or HGF.

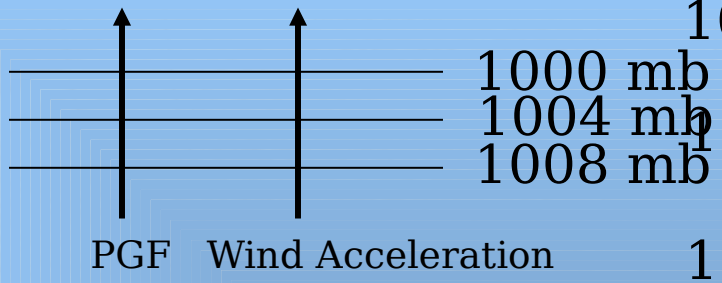
1 ⇑ PGF = ⇑ Wind Acceleration → (Results in Stronger wind speed.)

2 ⇓ PGF = ⇓ Wind Acceleration → (Results in weaker wind speed.)

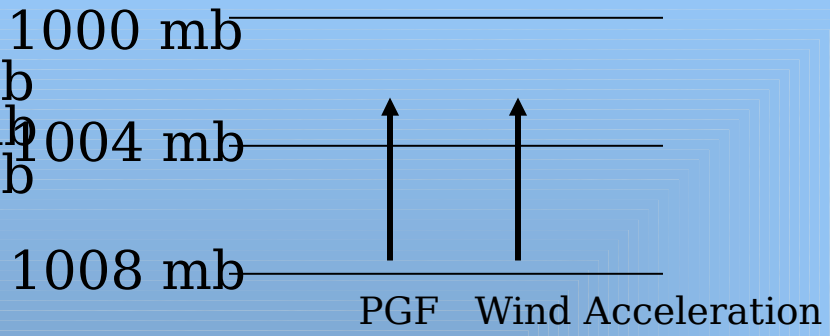
3 ⇑ HGF = ⇑ Wind Acceleration → (Results in stronger wind speed.)

4 ⇓ HGF = ⇓ Wind Acceleration → (Results in weaker wind speed.)

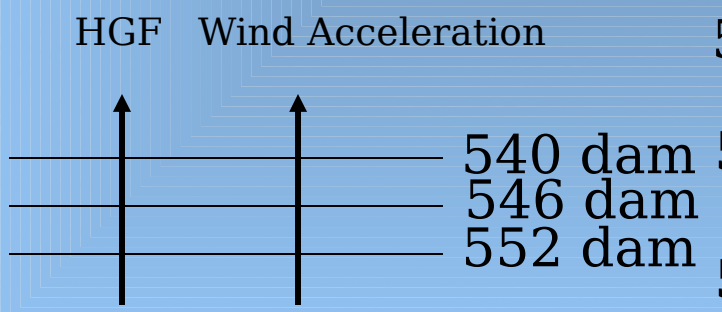
- The PGF (or HGF) is the force that generates wind motion, but rarely does this force act alone. The presence of additional forces changes the behavior of the wind.



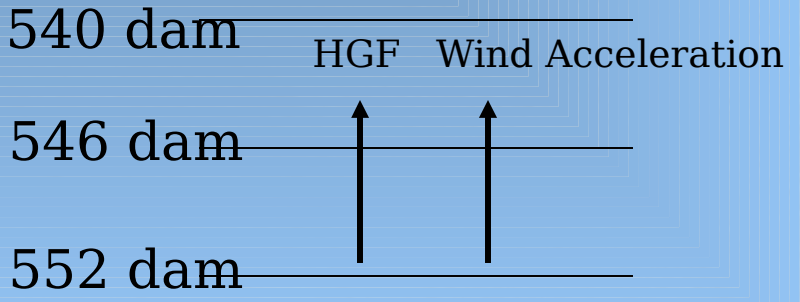
a. Strong PGF
Strong Acceleration



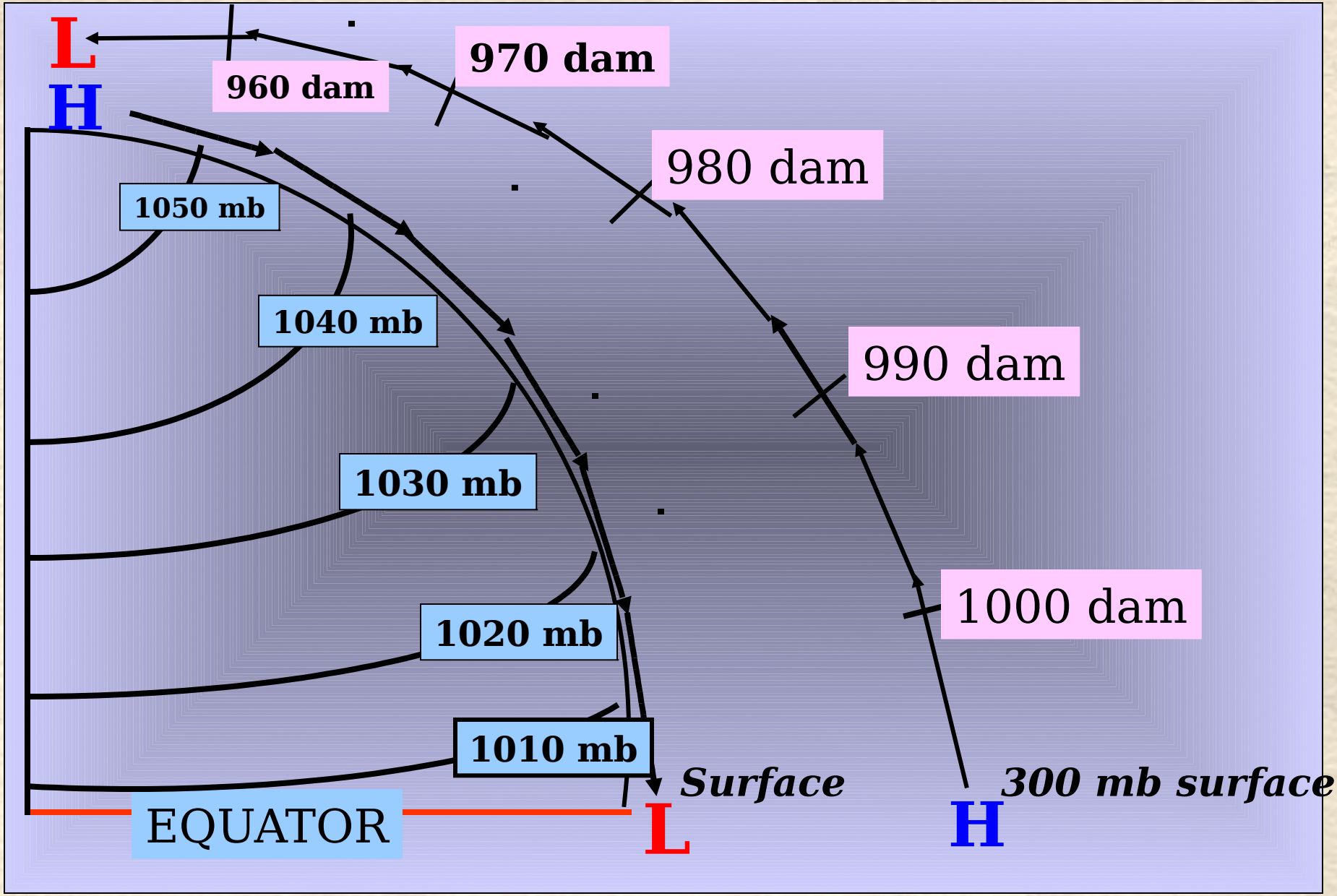
b. Weak PGF
Weak Acceleration



a. Strong HGF
Strong Acceleration



b. Weak HGF
Weak Acceleration


L
H
960 dam
970 dam
980 dam
990 dam
1000 dam
1050 mb
1040 mb
1030 mb
1020 mb
1010 mb
EQUATOR
Surface
300 mb surface
L
H

Coriolis Force (CoF):

- Apparent force exerted on moving objects (not fixed to Earth) caused by the rotation of the Earth and its coordinate system.
- Equal to the product of the coriolis parameter “f” and the linear velocity “V”.
  - Equation: **CoF = fV**
  - "f” is equal to 2 Ω sin(θ), where Ω is the Earth's angular velocity, a constant, and θ is the latitude.

Coriolis Force (CoF):

- Since the sine of 0° latitude = 0 and the sine of 90° = 1. CoF = 0 at the equator and increases as you move poleward. This variation in the CoF with latitude has a major implications in wind behavior across the globe.

Do some basic calculations of f at various latitudes. (Use calculators with sine function)

$$f = 2\,\Omega \sin(\theta),$$

- ***0° =***
- ***30° =***
- ***45° =***
- ***60° =***
- ***90° =***

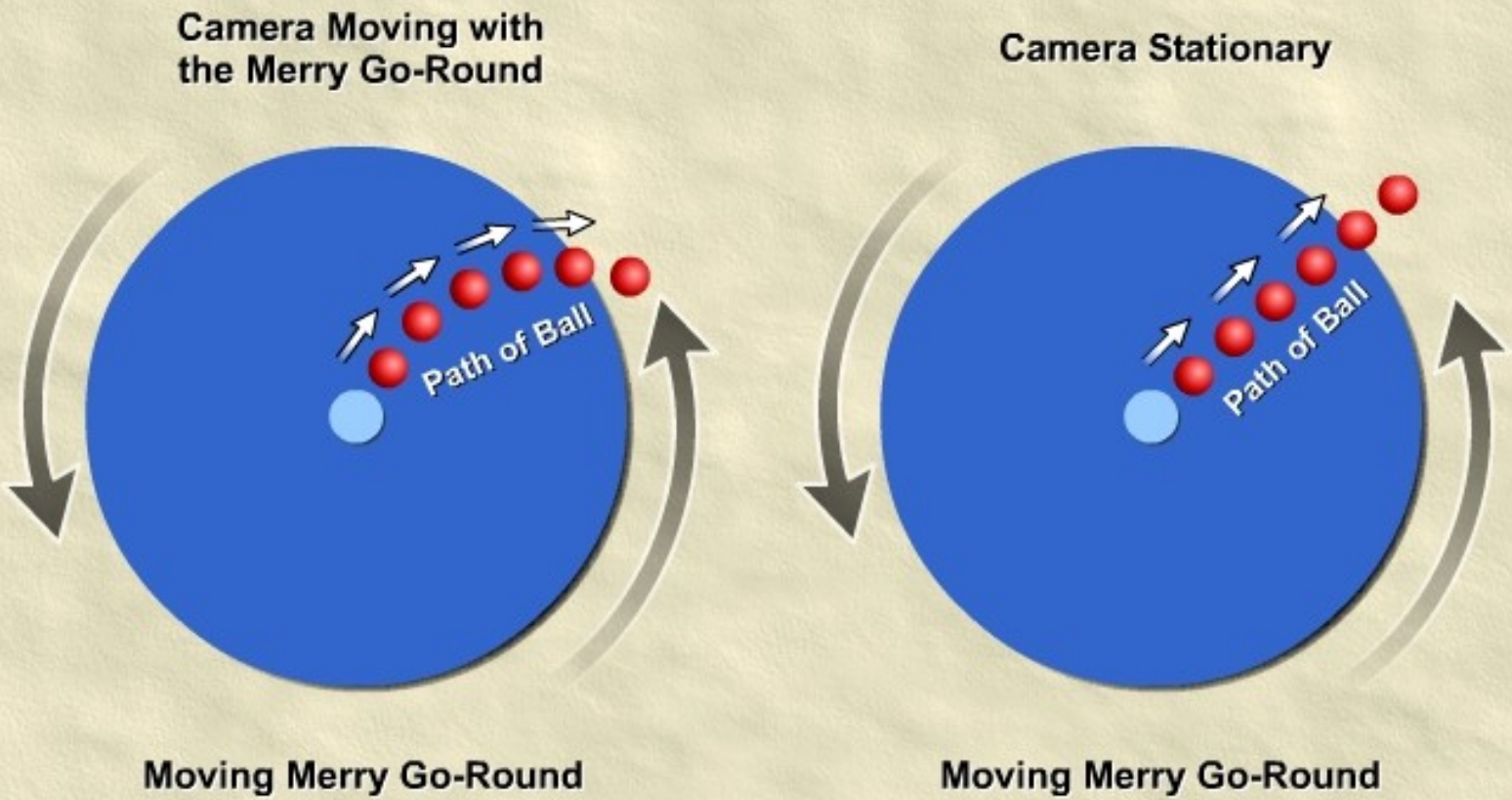
Coriolis Force (CoF):

- Also dependent on velocity. If "f" is constant (i.e., constant latitude) and CoF = fV, as velocity increases, CoF increases and as velocity decreases, CoF decreases.

Coriolis Force (CoF):

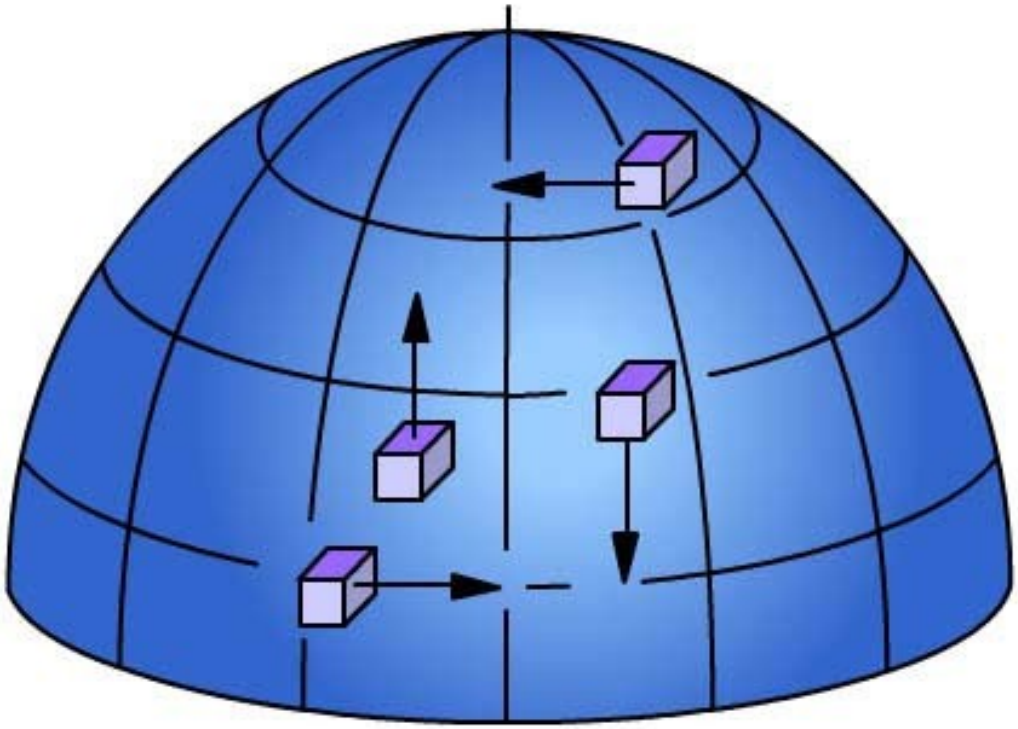
- To an observer on a star in space (considered a fixed location relative to the rotating Earth) an air parcel moves in a straight line when other forces acting upon the parcel are in balance.

Coriolis Effect



TR: Observing spinning platform from above.

PARCEL MOTION AS SEEN FROM THE STARS

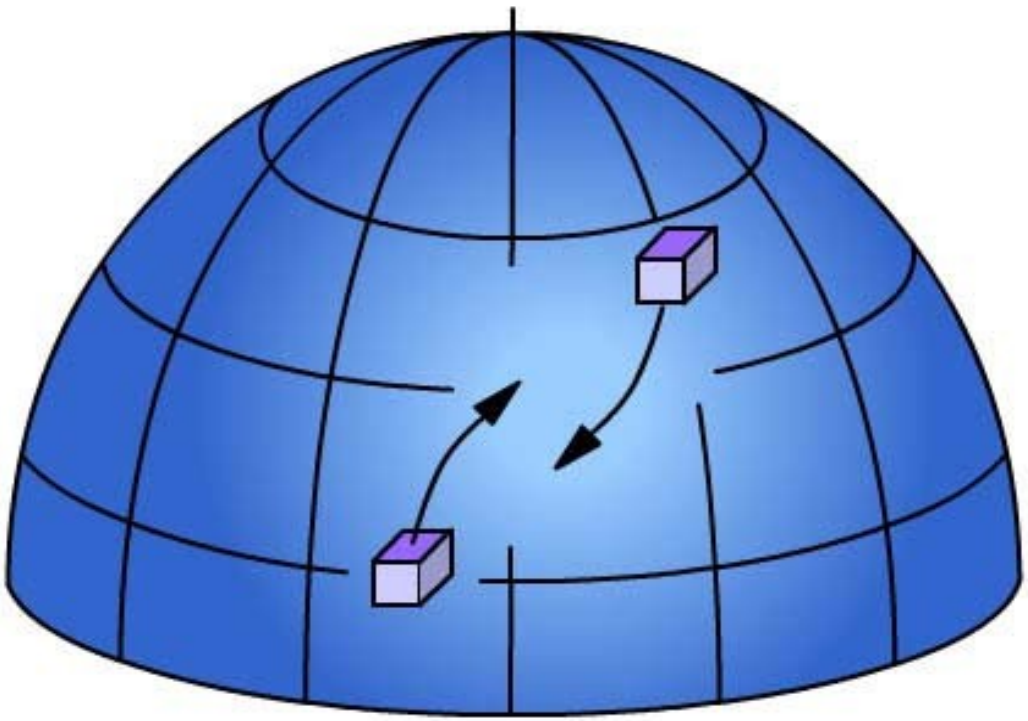


AS SEEN FROM A STAR

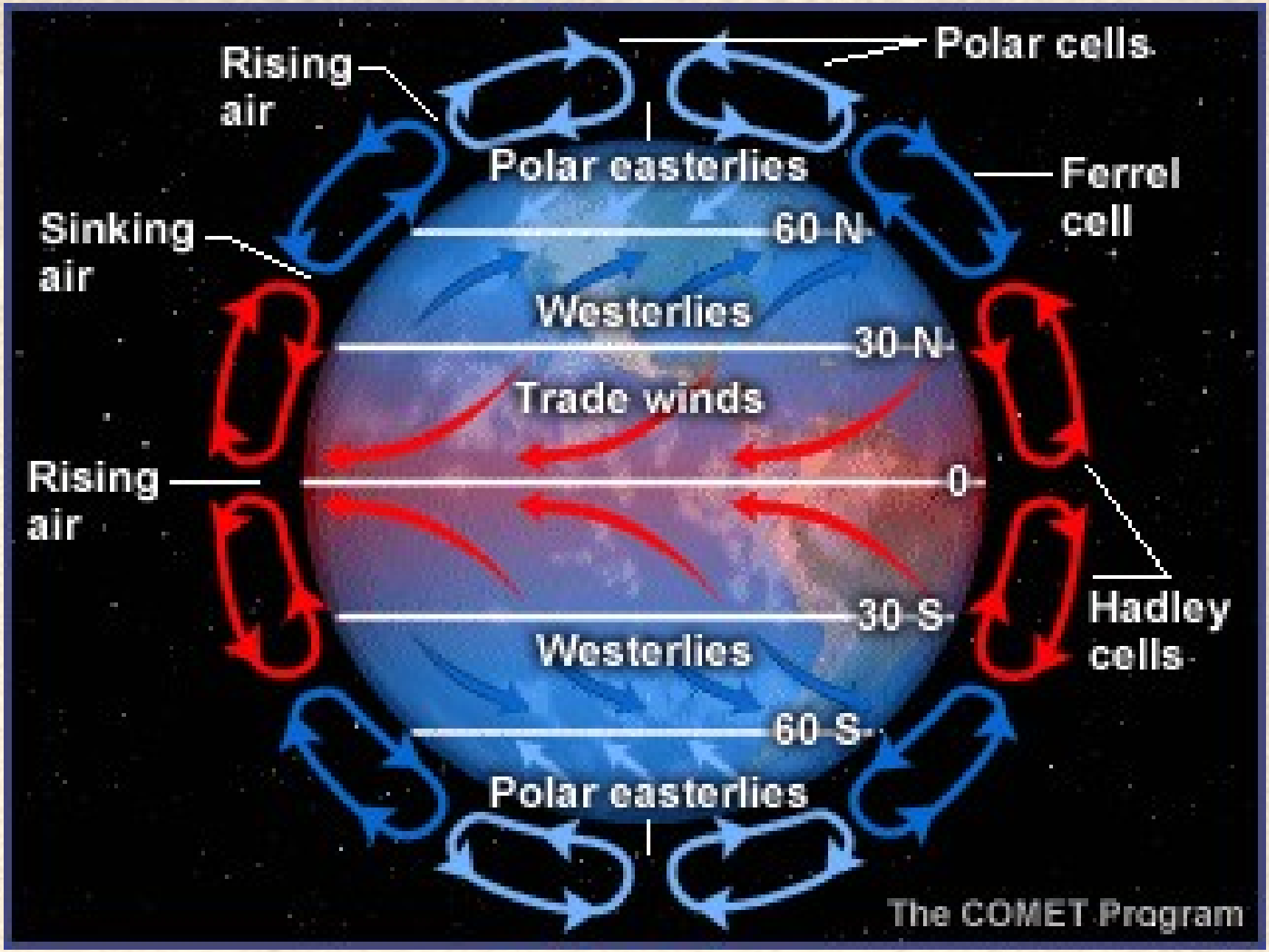
Coriolis Force (CoF):

- To an observer on the GOES satellite which rotates with the Earth's coordinate system, (Lat./Long), or to an observer on the Earth, air parcels are deflected to the right of motion in the Northern Hemisphere and to the left of motion in the Southern Hemisphere.
  - **Always** acts 90° to wind direction.
    - » In the -n direction (to the right of parcel motion) in the Northern Hemisphere
    - » In the +n direction (to the left of parcel motion) in the Southern Hemisphere.
  - The closer you get to the poles, the stronger the CoF.

PARCEL MOTION AS SEEN BY EITHER AN OBSERVER ON EARTH OF **G O E S** SATELLITE ROTATING WITH THE EARTH.



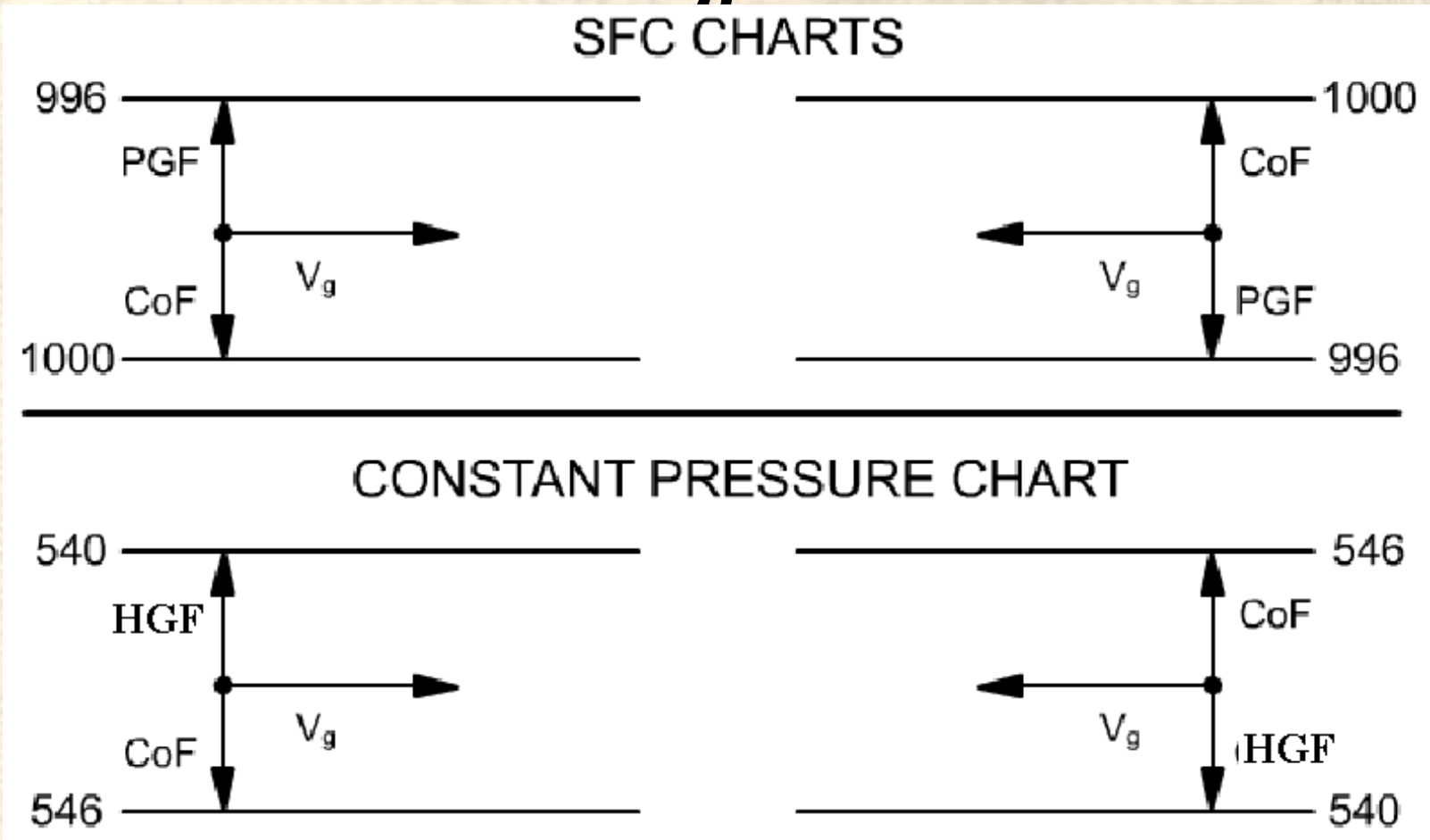
AS SEEN FROM A **G O E S**


Rising air
Polar cells
Polar easterlies
Ferrel cell
Sinking air
60 N
Westerlies
30 N
Trade winds
Rising air
0
30 S
Hadley cells
Westerlies
60 S
Polar easterlies
The COMET Program

Geostrophic wind (V_g)

- Definition – The wind which results from a balance between the PGF (or HGF) and CoF.
  - Assumes Straight Line Flow (i.e., no curvature) where PGF and CoF are equal and opposite to one another.
    - (i.e., Term A in Eq 2 must be zero because no radius of curvature is allowed).

Forces which produce V_g



Geostrophic wind (V_g)

- Assumes **No friction forces**
  - No frictional force (Fr = 0)
  - Becomes more geostrophic above earth's surface as friction decreases.
- Assumes a constant wind speed
  - (i.e., Term A (acceleration) in Eq 1 must be zero; therefore, equation (1) does not influence V_g flow.)

Geostrophic wind (V_g)

- With the above assumptions, Eq. (1) is eliminated, and only Terms B and C in Eq. (2) remain. Therefore, only these two remaining terms in Eq. 2 describe V_g flow. (Note: Boxed items indicate the terms remaining to describe V_g flow.)

Geostrophic wind (V_g)

$$\frac{\Delta V}{\Delta t} = -\frac{1}{\rho}\frac{\Delta P}{\Delta s} \qquad (1)$$

(A) (B)

$$\frac{V^2}{r} + fV = -\frac{1}{\rho}\frac{\Delta P}{\Delta n} \qquad (2)$$

(A) (B) (C)

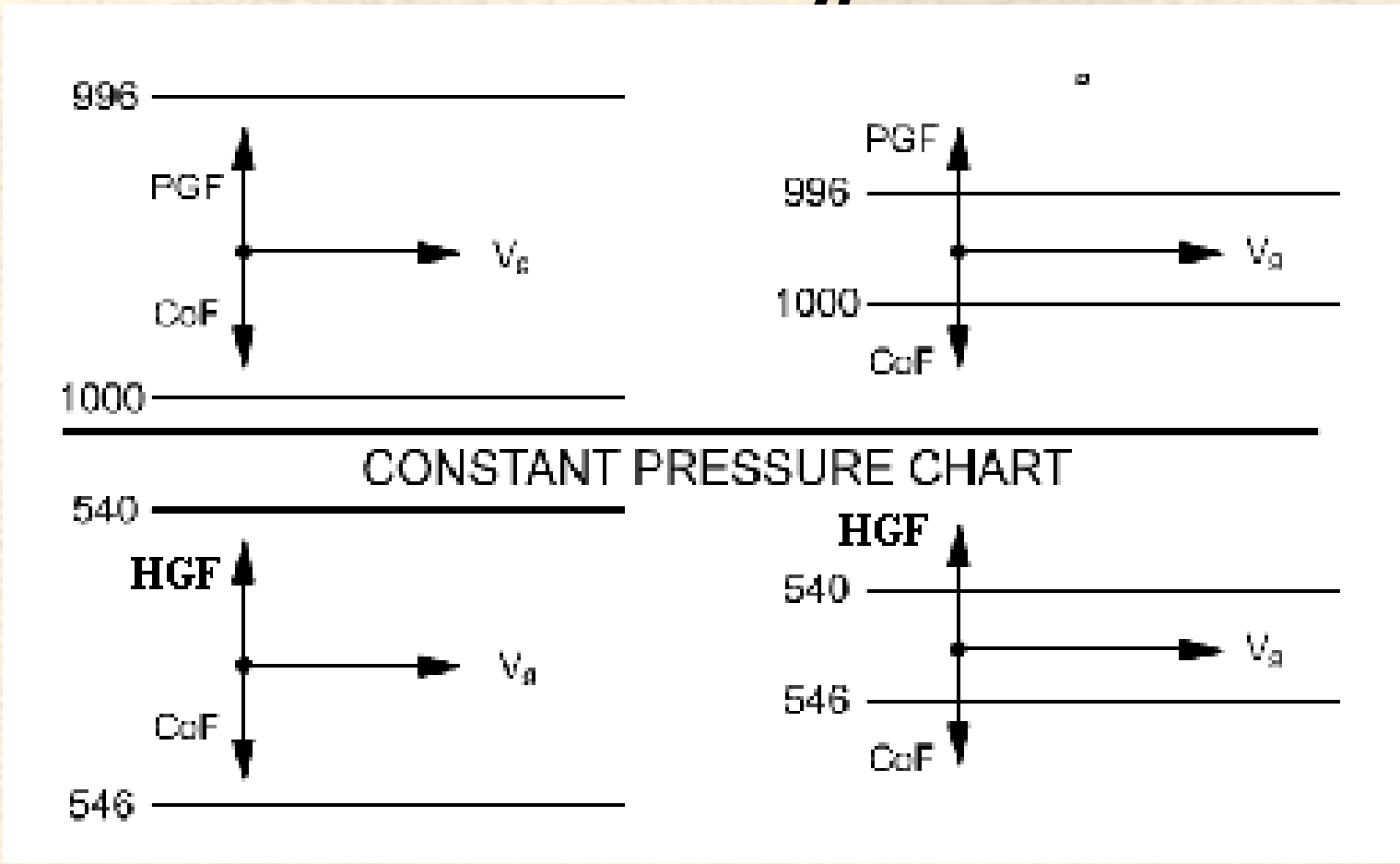
Geostrophic wind (V_g)

- Therefore, the equation for V_g flow becomes (Note: V is set to V_g).

$$V_g = \frac{-1}{f\rho}\frac{\Delta P}{\Delta n} \qquad (2)$$

- The closer the isobars/height contours are, the stronger the geostrophic winds. With an increase in PG or HG, PGF or HGF increases.

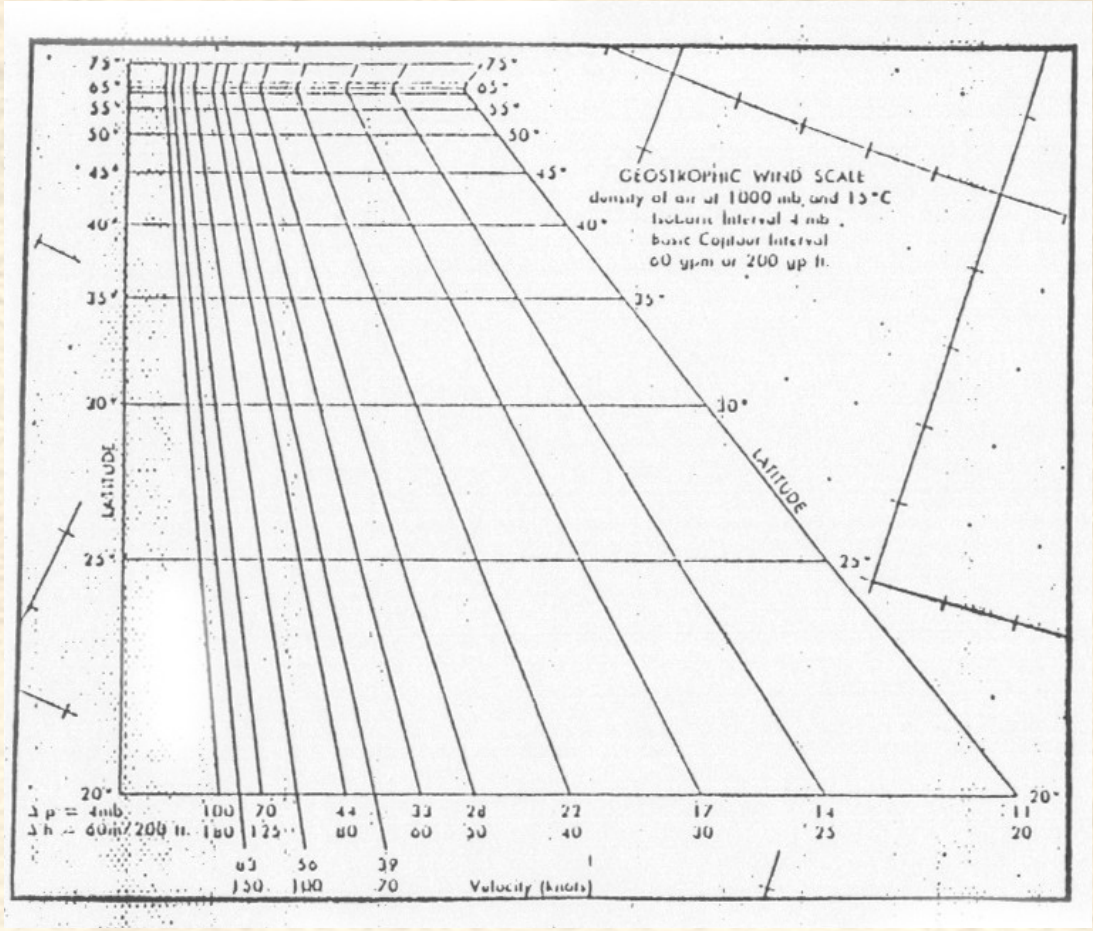
Effects of PGF or HGF on V_a



Geostrophic wind (V_g)

- The Geostrophic Wind Scale, shows PGF (or HGF) vs. latitude.
  - In V_g conditions with a constant PGF, the CoF vector must equal and directly oppose the PGF vector to maintain balance. Since the magnitude of the CoF=fV any change in "f" means a change must occur to "V". Thus the product of "f" and "V" must balance the magnitude of the PGF.

Geostrophic Wind scale depicting V_g

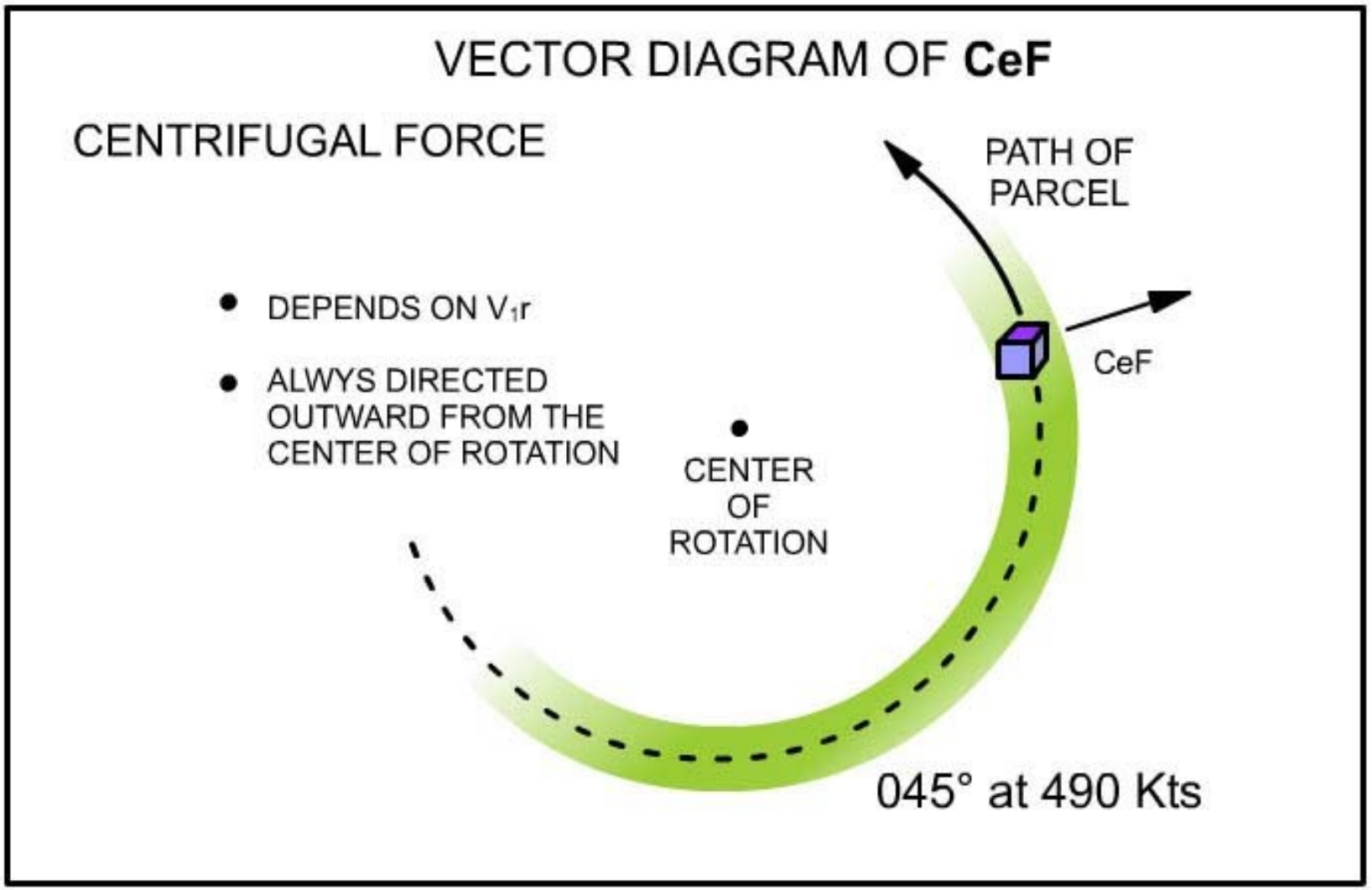


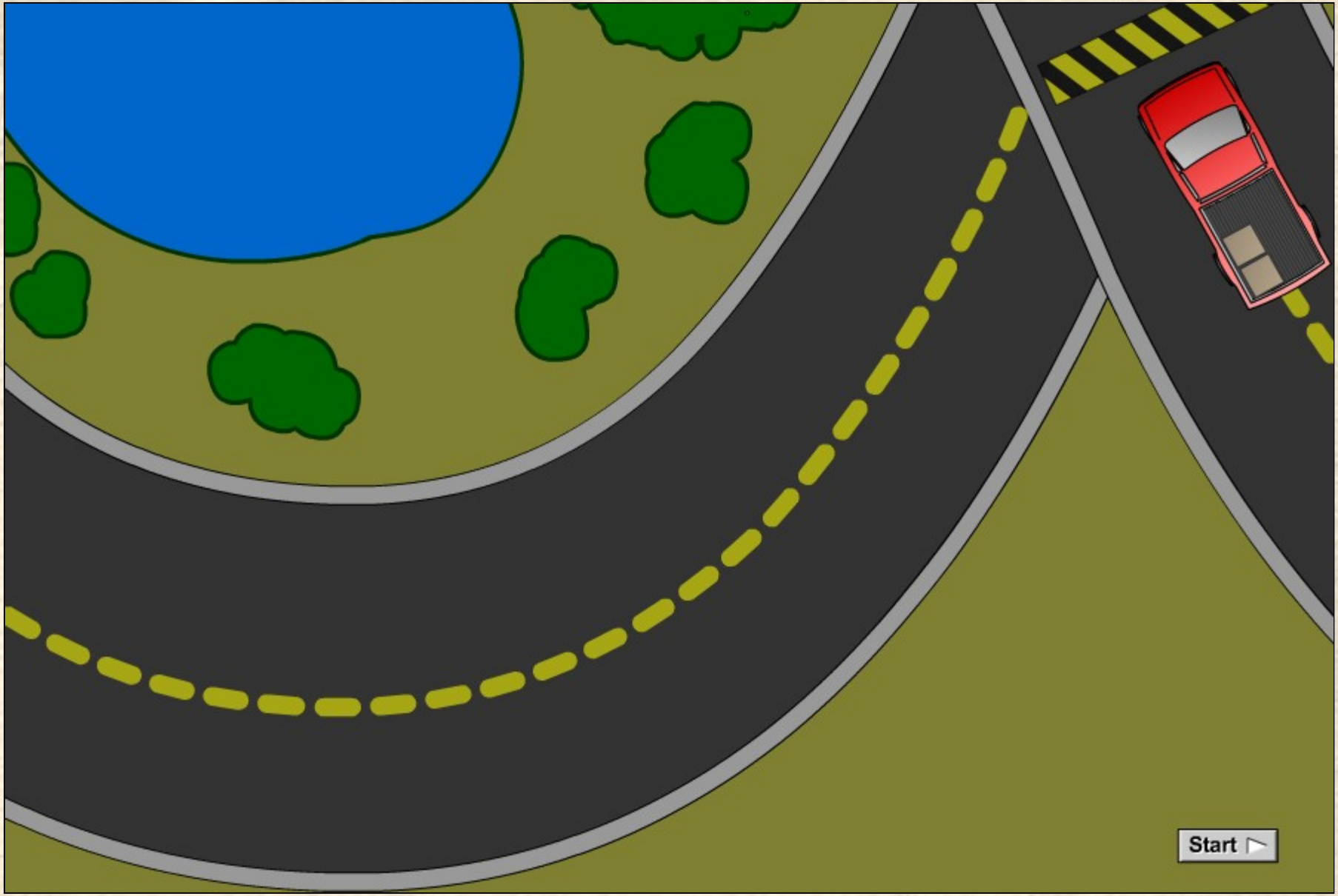
Geostrophic wind (V_g)

- For a constant PGF, V_g increases equatorward
  - "f" decreases
  - Requires an increase in "V" to keep CoF/PGF in balance.
  - **|CoF| =** f⇓ V therefore, **PGF = CoF**. So, V_g is stronger at 30° than 60 ° (for same PGF or HGF).
- Geostrophic wind scale
  - Used to manually determine approximate wind speeds in data sparse areas.

Centrifugal Force (CeF)

- Apparent force in curved flow that deflects particles and therefore wi nds away from the center of rotatio n. (e.g., The apparent force which pushes you to the outside of the turn as your car goes around a curve.)
- **Always** directed outward from axis of rotation, perpendicular to V.
- Describes the balance of forces present with winds in curved flow

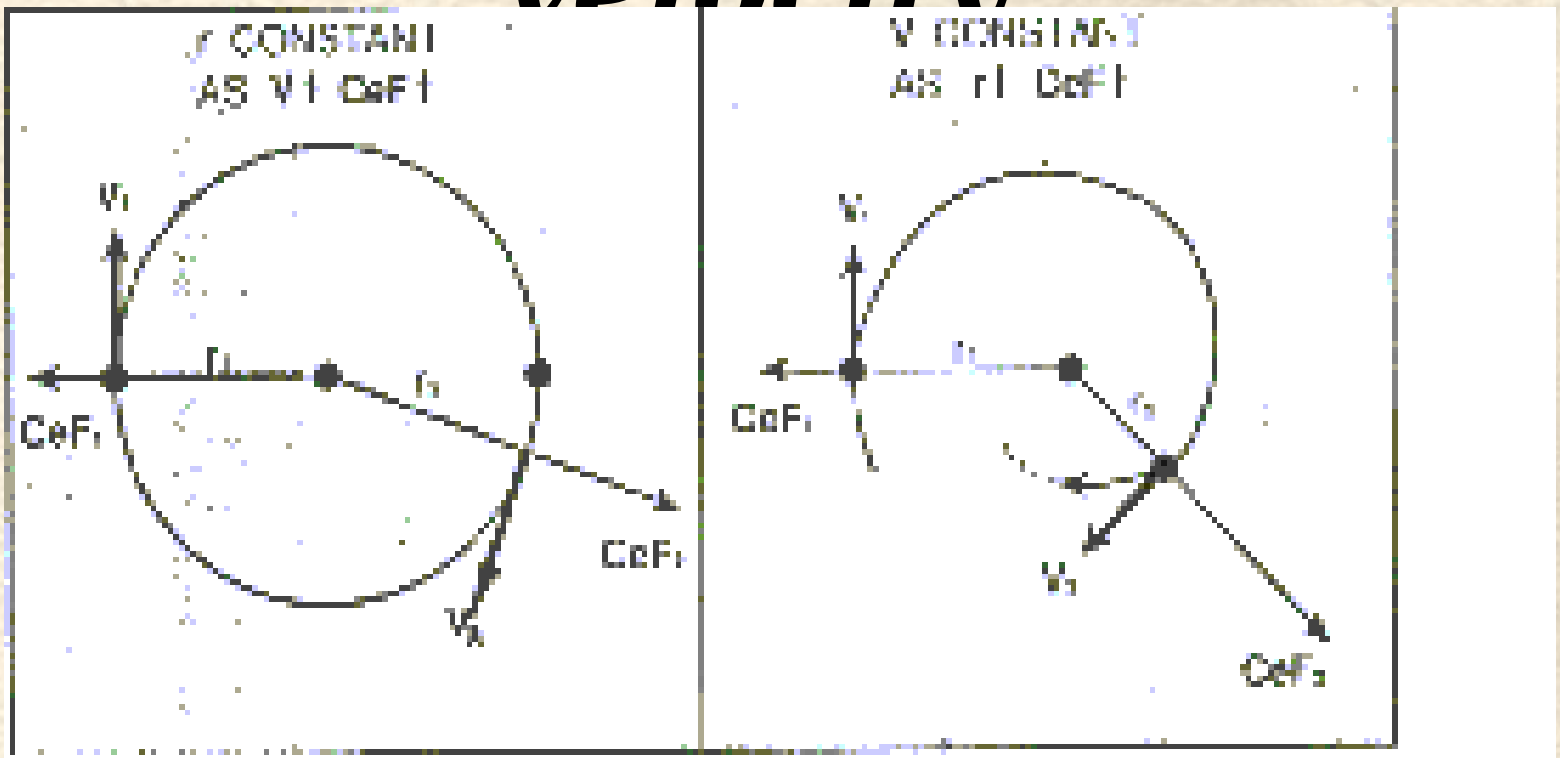

VECTOR DIAGRAM OF CeF
CENTRIFUGAL FORCE
PATH OF PARCEL
DEPENDS ON V1r
ALWYS DIRECTED OUTWARD FROM THE CENTER OF ROTATION
CeF
CENTER OF ROTATION
045° at 490 Kts


Start

Centrifugal Force (CeF)

- Strength dependent on two factors.
  - Velocity
    - The smaller the velocity of a moving parcel, the smaller the CeF for a constant curvature
    - The greater the velocity of a moving parcel, the greater the CeF for a constant curvature.

PPT: CeF's relationship to curvature and velocity



Centrifugal Force (CeF)

- Radius
  - As radius of curvature increases, velocity and CeF decreases.
  - As radius of curvature decreases, velocity and CeF increases.
- Equation: $\mathbf{CeF = \frac{mV^2}{r}}$

Inertial Wind (V_i)

Active Forces: CoF and CeF

- Definition – Inertial wind is a flow which occurs when the CoF is balanced by an opposing CeF.
- A wind that results if air flow enters a region where PGF (or HGF) vanishes, while CoF remains significant. As the wind curves in the direction of the CoF, an opposing CeF develops and eventually balances CoF.

Inertial Wind (V_i)

- The lack of a PGF eliminates Term C in Eq. 2 from influencing. V_i.
- Thus, only Terms A and B in Eq. 2 govern V_i. (Note: Boxed items indicate the terms remaining to describe V_i flow.)

Inertial Wind (V_i)

$$\frac{\Delta V}{\Delta t} = -1\,\frac{\Delta P}{\rho\,\Delta s} \qquad (1)$$

(A) **(B)**

$$\frac{V^2}{r} + fV = -1\,\frac{\Delta P}{\rho\,\Delta n} \qquad (2)$$

(A) **(B)** **(C)**

Inertial Wind (V_i)

- Therefore, with a simple algebraic manipulation of these remaining terms, the equation for V_i flow becomes (Note: V is set to $V_{i)}$: **$r = -V_i / f$**
- According to this equation, the inertial motion's radius of curvature depends on two factors

Inertial Wind (V_i)

$$r = -V_i / f$$

– Latitude (assuming constant velocity)

- As latitude decreases, the CoF weakens, thus, radius of curvature increases (i.e., the parcel describes a broader loop).
- As latitude increases, the CoF strengthens; thus the radius of curvature decreases (i.e., the parcel describes a tighter loop)..

Inertial Wind (V_i)

$$r = -V_i / f$$

– Velocity (assuming constant latitude)

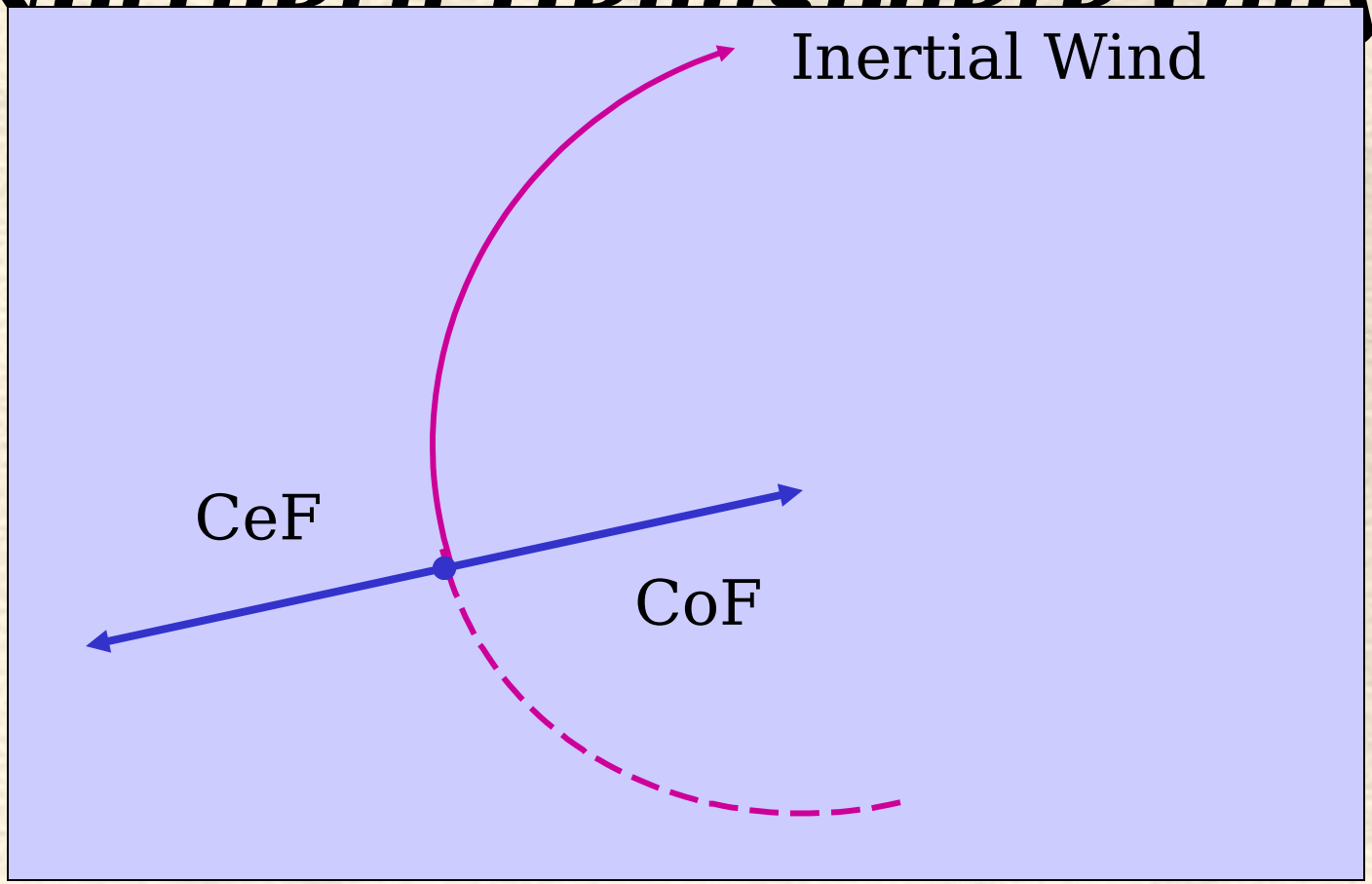
- As velocity increases, the radius of curvature increases
- As velocity decreases, the radius of curvature decreases

Inertial Wind (V_i)

- Note: Very rarely does PGF vanish in the real atmosphere; thus, actual conditions are rarely met for true inertial wind flow. This type of motion is much more common in ocean currents

Wind Flow in V_i balance

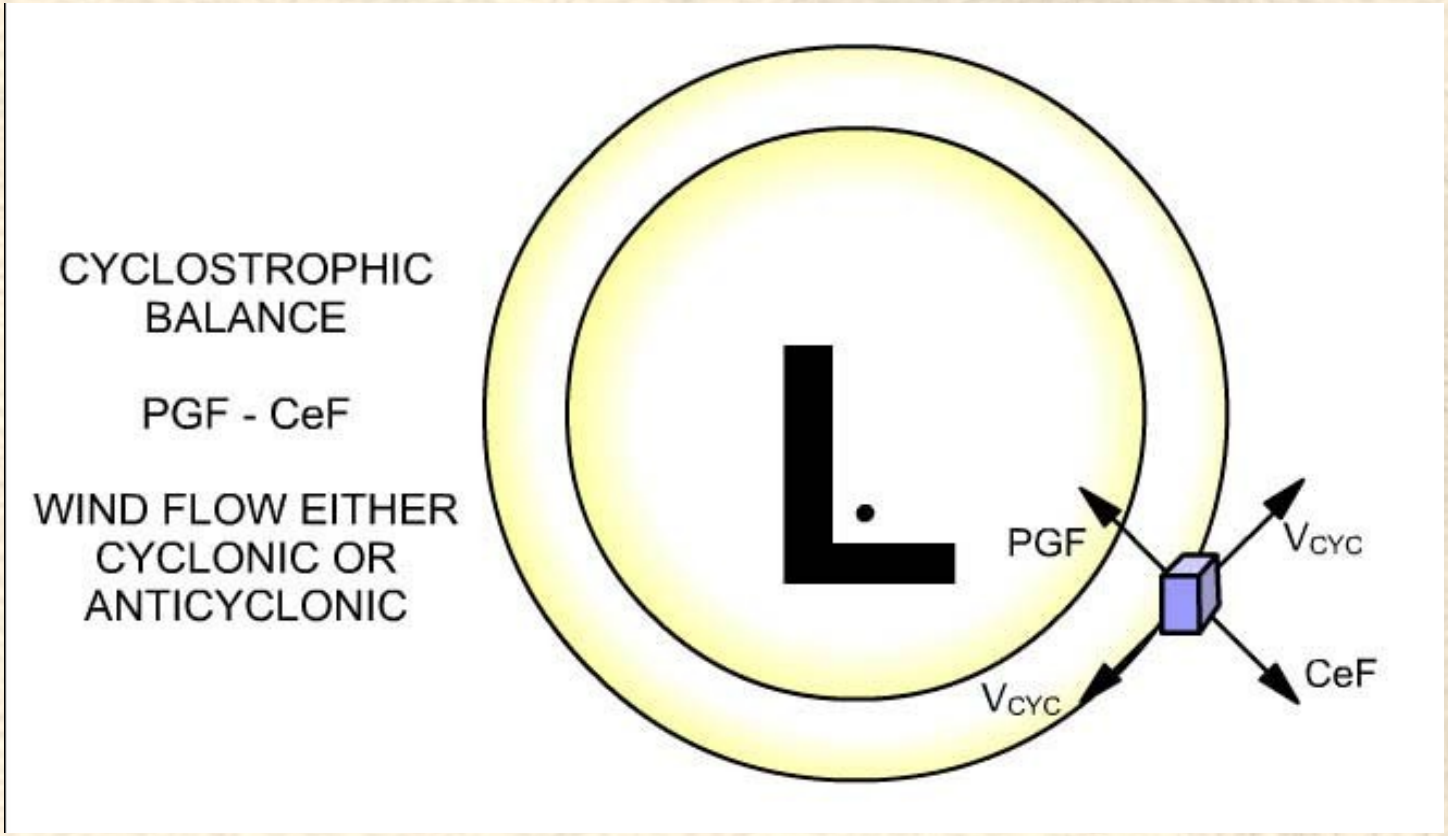
Northern Hemisphere Only



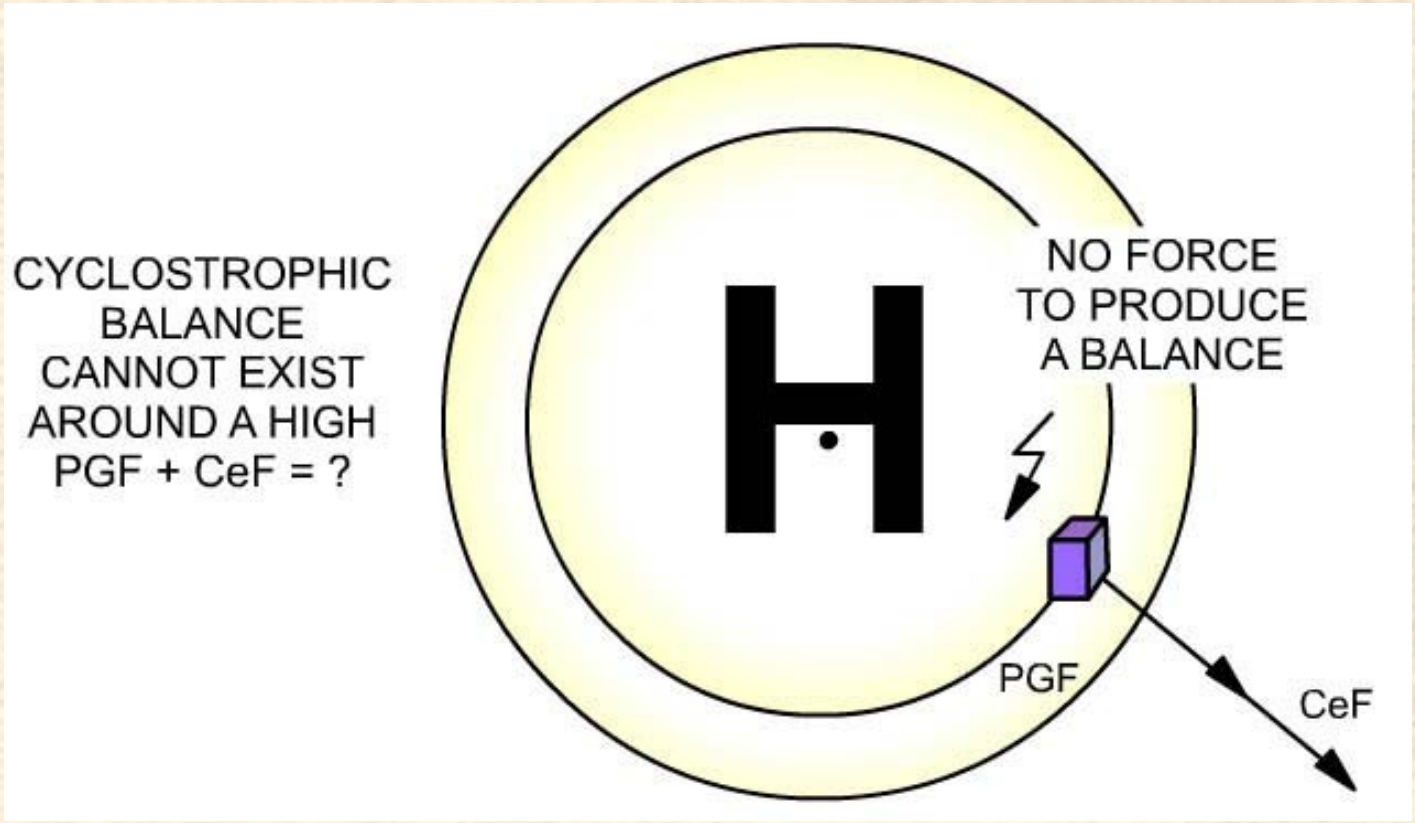
Cyclostrophic Wind (V_{cyc})

- Definition – a wind that occurs when PGF or HGF is balanced by **CeF. CoF** is negligible when compared to PGF, HGF, or CeF.

Vector diagram of winds around a low



Vector diagram of winds around a high



Cyclostrophic Wind (V_{cyc})

- Examples of cyclostrophic wind flow in the real atmosphere

  - Generally, cyclostrophic flow is only possible for rather small systems (CoF does not have much influence on small short-lived systems)..

Cyclostrophic Wind (V_{cyc})

- In the mid-latitudes, cyclostrophic flow is most common for systems with a very strong PGF and a small radius of rotation, resulting in a large CeF: (i.e., dust devils, tornadoes and waterspouts).
  - **Due to the extreme PGF/HGF, intense V_{cyc} flow is possible in either clockwise or counterclockwise directions around these small scale low pressure systems.**

Gradient Winds

- Definition – Winds that would result if there were a balance between PGF, CoF, and CeF in curved flow.

Gradient Winds

- Three assumptions must be made about the gradient wind balance:
  - Assumes winds blow parallel to the height (pressure) contours.
  - Assumes **NO FRICTION** (Fr = 0). Best observed above the boundary layer where friction is near zero.
  - Assumes curvature in the wind flow, therefore CeF is important.

Gradient Winds

- Thus, all Terms (A, B, and C) in Eq.2 govern V_{grad}

(Note: Boxed items indicate the terms describing V_{grad} flow.)

$$\frac{\Delta V}{\Delta t} = -\frac{1}{\rho}\frac{\Delta P}{\Delta s} \quad (1)$$

(A) **(B)**

$$\boxed{\frac{V^2}{r} + fV} = -\frac{1}{\rho}\frac{\Delta P}{\Delta n} \quad (2)$$

(A) **(B)** **(C)**

Gradient Winds

- Algebraically manipulating these terms and solving for V in term A, the equation for V_{grad} flow becomes (Note: V is set to V_{grad}):

$$V_{grad} = -\frac{fr}{2} \pm \sqrt{\frac{f^2 r^2}{4} - r\frac{1}{\rho}\frac{\Delta P}{\Delta n}}$$

Although there are several solutions to the above equation, only two of the most common will be discussed here.

Gradient Winds

- Since most flow in the atmosphere is curved, the gradient wind is a better estimate of the true wind than is the geostrophic wind. The geostrophic approximation of the wind is inaccurate when the flow is curved. CeF must be balanced by an increase or decrease in the actual wind.

Gradient Winds

- In cyclonically-curved flow, V_g is OVERestimated (i.e., actual wind in a trough are less than geostrophic wind speed).

- In anticyclonically-curved flow, V_g is UNDERestimated (i.e., actual winds in a ridge are greater than geostrophic wind speed)

In these curved-flow situations, V_{grad} is a better indication of the true wind than is V_g.

- Supergeostrophic gradient wind ($V_{grad,\ anticyc}$).
  - Wind of greater speed than geostrophic wind required by existing PG/HG at same latitude.
  - Found in anticyclonic flow
  - **CoF = HGF + CeF.**

Gradient Winds

- Subgeostrophic Gradient Wind ($V_{grad,cyc}$).
  - Wind of <u>lesser speed</u> than geostrophic wind required by existing PG/HG at same latitude.
  - Found in cyclonic flow
  - HGF = CoF + CeF

Comparison of straight flow to curved flow wind speeds

$V_a = V_g + CEF$ and $V_c = V_g - CEF$

HGF = HEIGHT GRADIENT FORCE

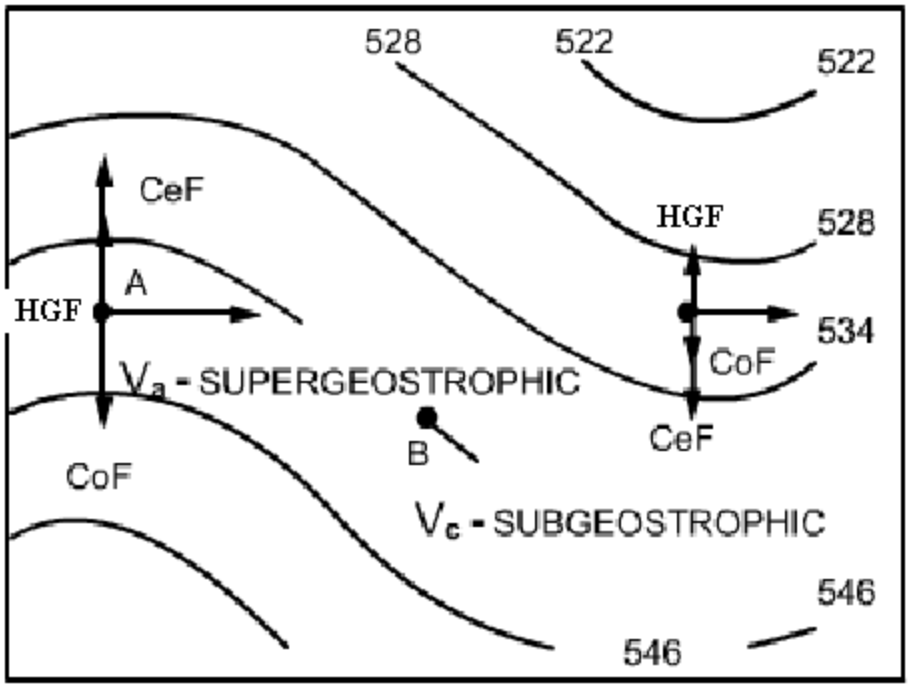
CoF = CORIOLIS FORCE

CeF = CENTRIFUGAL FORCE

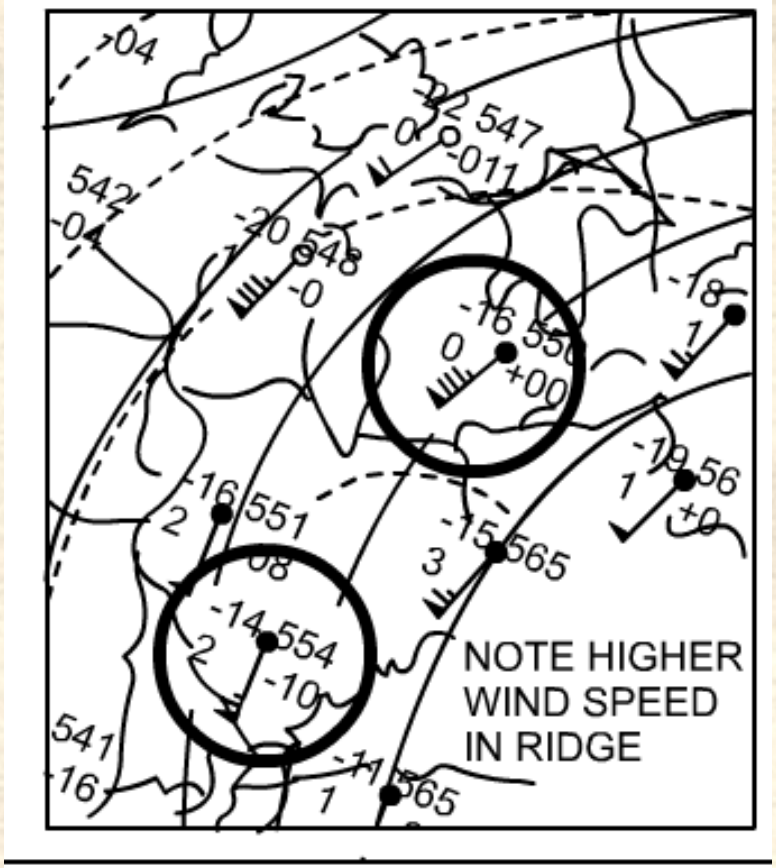
V_a = ANTICYCLONIC GRADIENT WIND (SUPERGEOSTROPHIC)

V_g = GEOSTROPHIC

V_c = CYCLONIC GRADIENT WIND (SUBGEOSTROPHIC)



Actual comparison of $V_{grad,\ anticyc}$ to V_g



Geostrophic/Gradient Wind Relationships

- For the same PG or HG and latitude
  - V_{grad} winds will be stronger in anticyclonic curvature
  - V_{grad} winds will be weaker in cyclonic curvature
  - **$V_{grad,\ anticyc} > V_g > V_{grad,cyc}$**

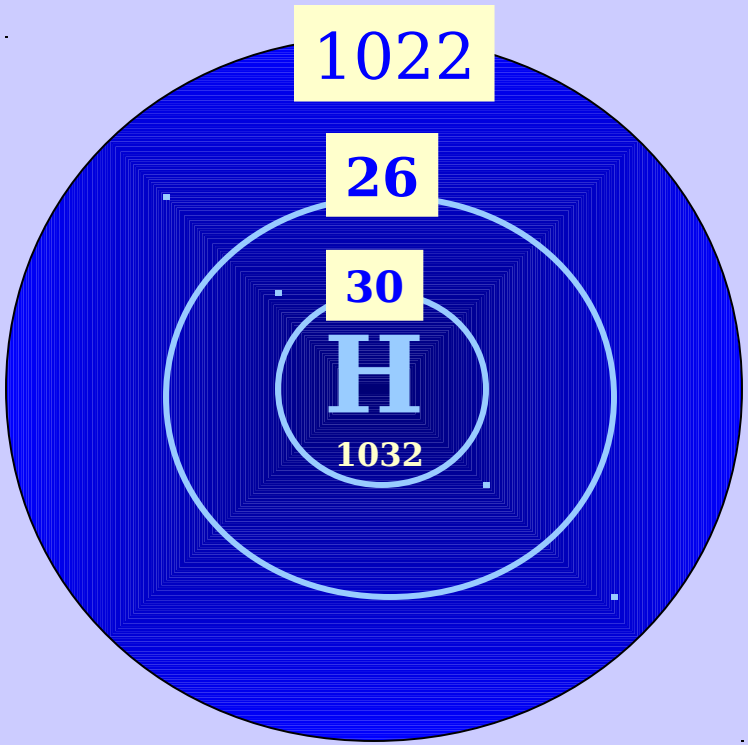
Geostrophic/Gradient Wind

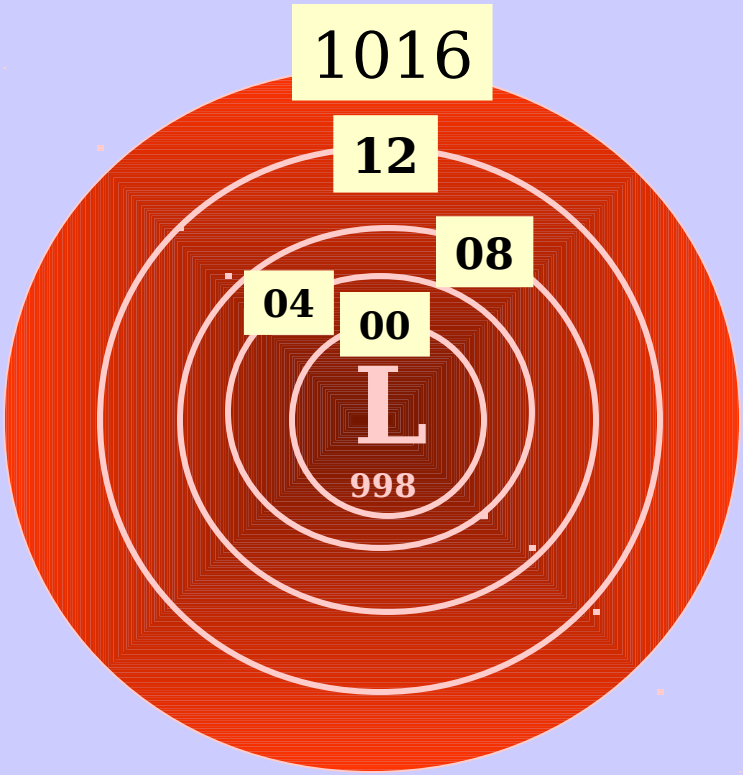
- There is a limit on how strong a PG/HG occur in anticyclonically curved flow.
  - If a PG/HG beyond this limit were to exist then

    (CeF + PGF) would exceed CoF and a balance could not be achieved.
  - Isobars/Height Contours in regions of strong anticyclonic curvature tend to be more widely spaced due to the stronger CeF advecting mass across the height contours form higher to lower values.

Geostrophic/Gradient Wind

- No such limit exists for cyclonically curved flow.
- The gradient wind relationship dictates that:
  - Anticyclones have broad centers of light winds with only a slow increase in wind speed allowed outward from the center.
  - Cyclones may have small concentrated circulation centers with sharp increases in wind speed allowed outward from the center. Thus, very strong winds can exist immediately surrounding the center (i.e., such as observed in the eye and eyewall of a hurricane).

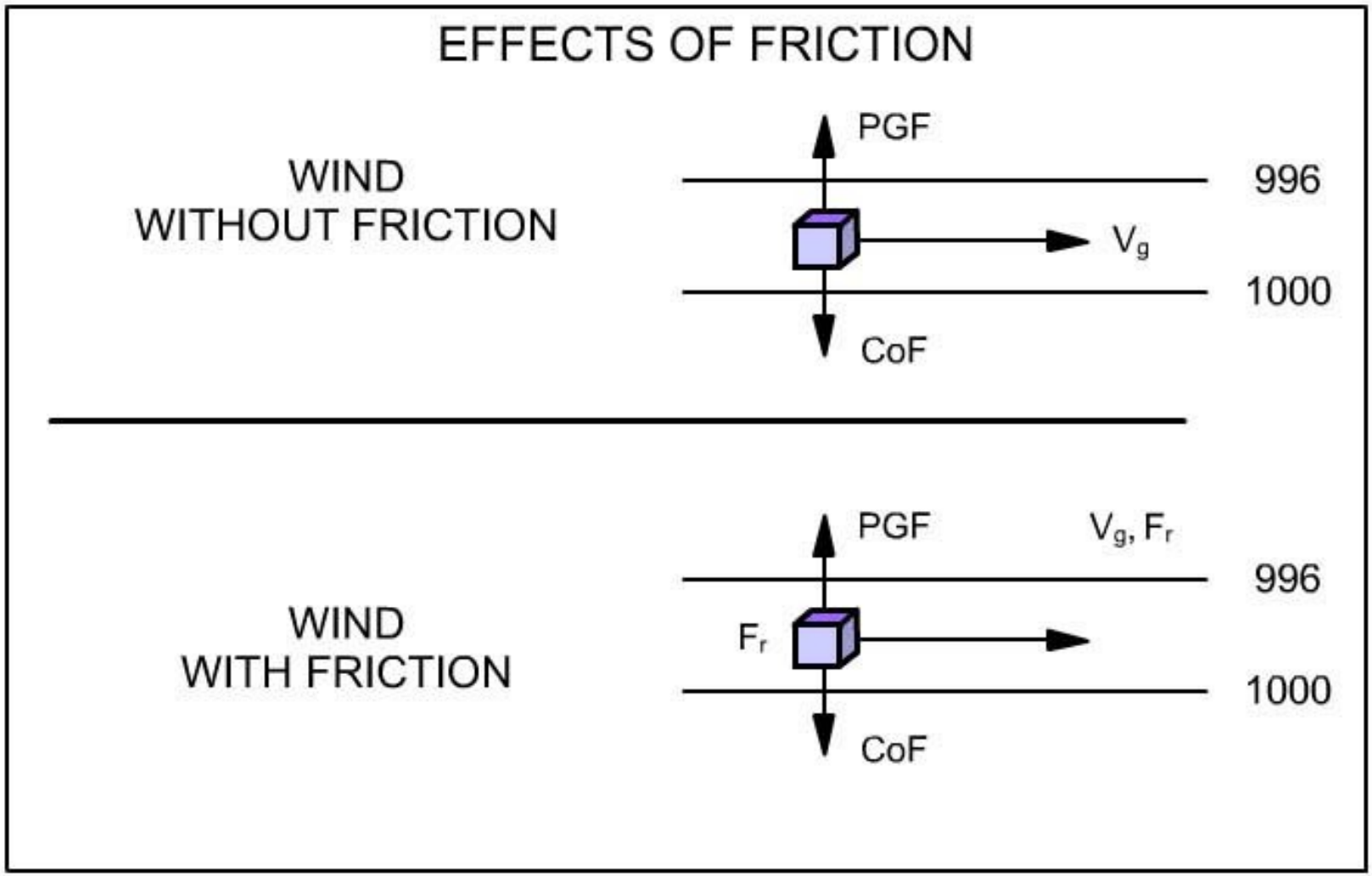

1022
26
30
H
1032


1016
12
08
04
00
L
998

Frictional Force (Fr)

- The force that opposes motion.
- **Always** acts opposite to direction of motion (wind direction).

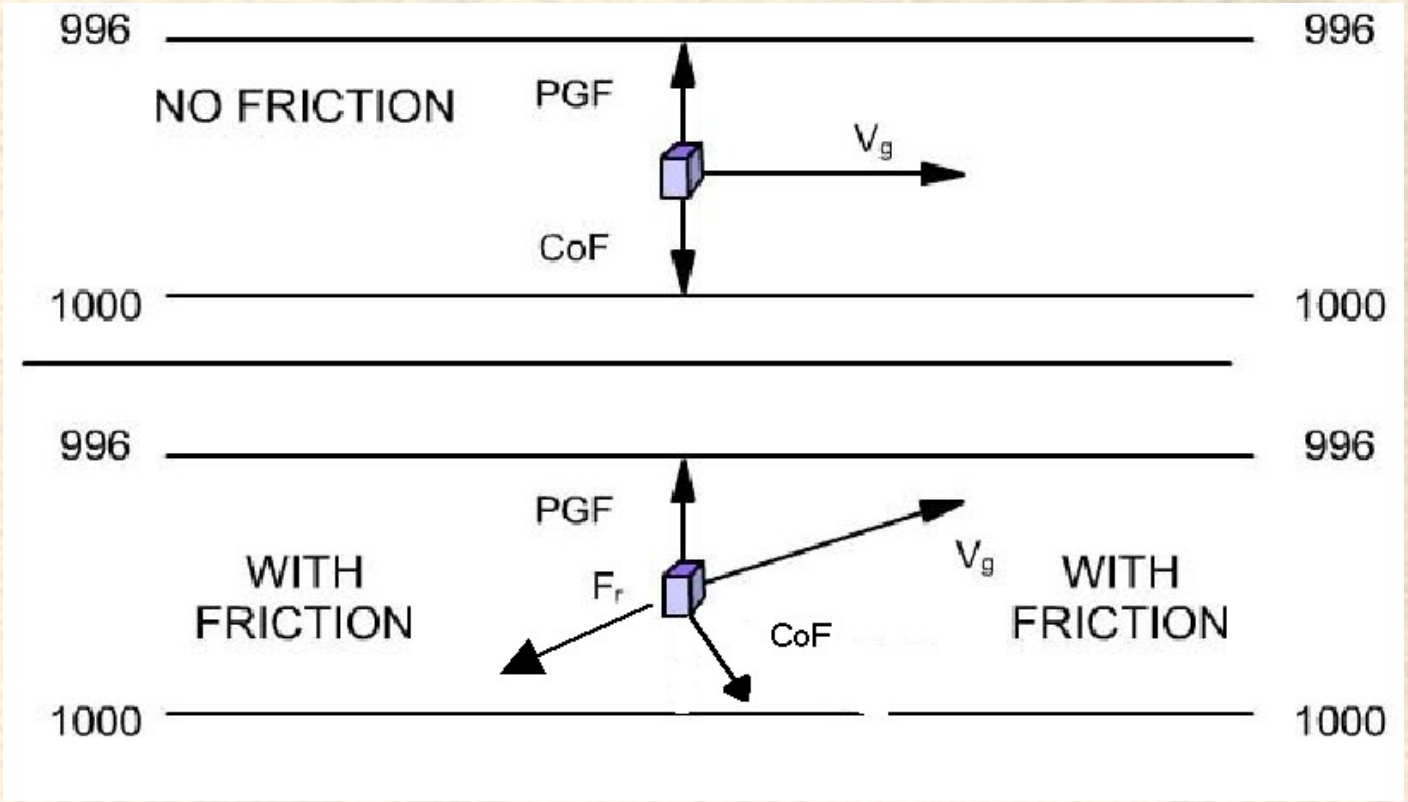
- Inversely proportional to wind velocity “V”


EFFECTS OF FRICTION
WIND
WITHOUT FRICTION
PGF
996
V_g
1000
CoF
WIND
WITH FRICTION
PGF
V_g, F_r
996
F_r
1000
CoF

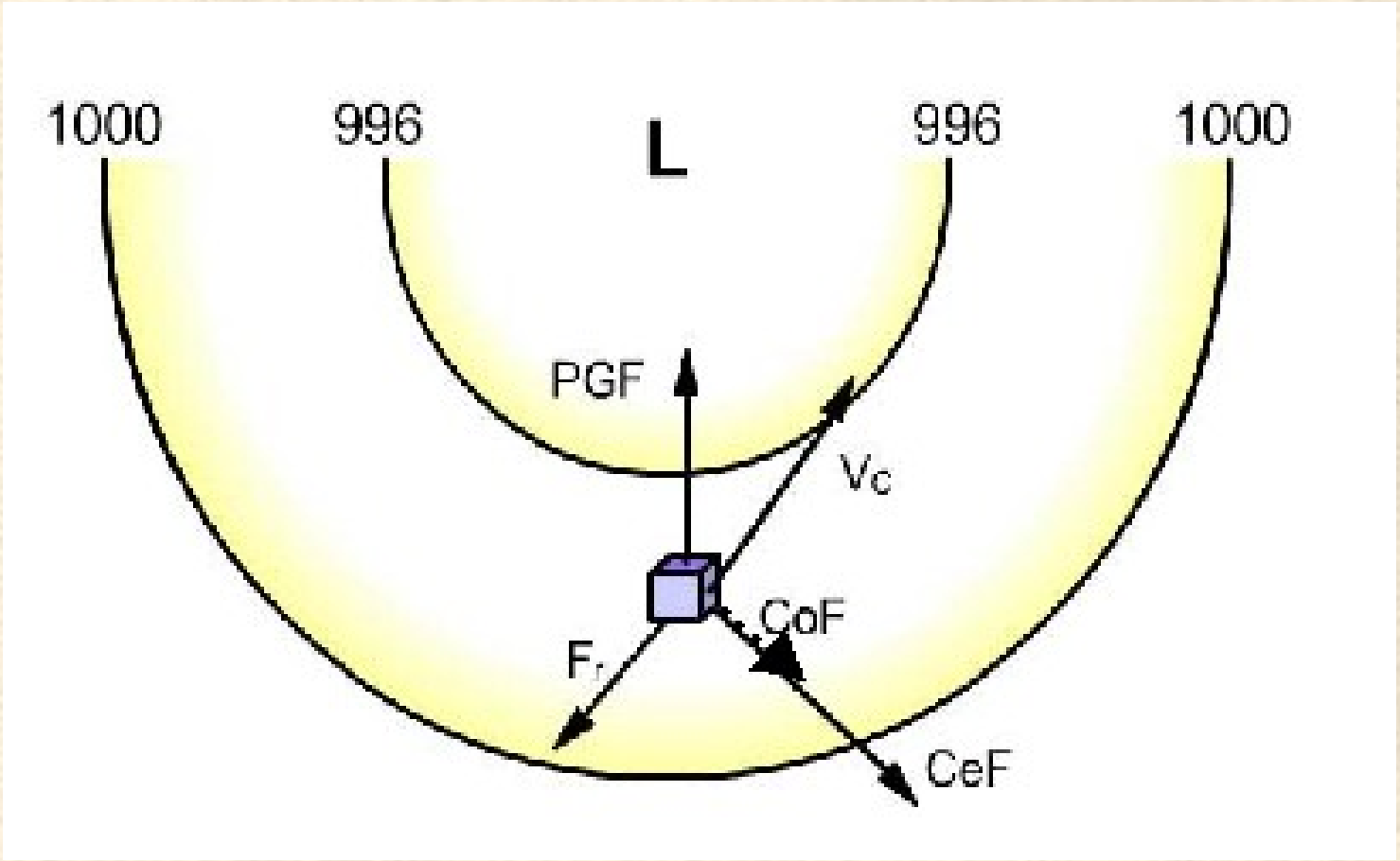
Frictional Force (Fr)

- Friction slows down the balanced geostrophic wind
- Friction destroys the balance of forces which create the geostrophic wind. Thus winds become ageostrophic.

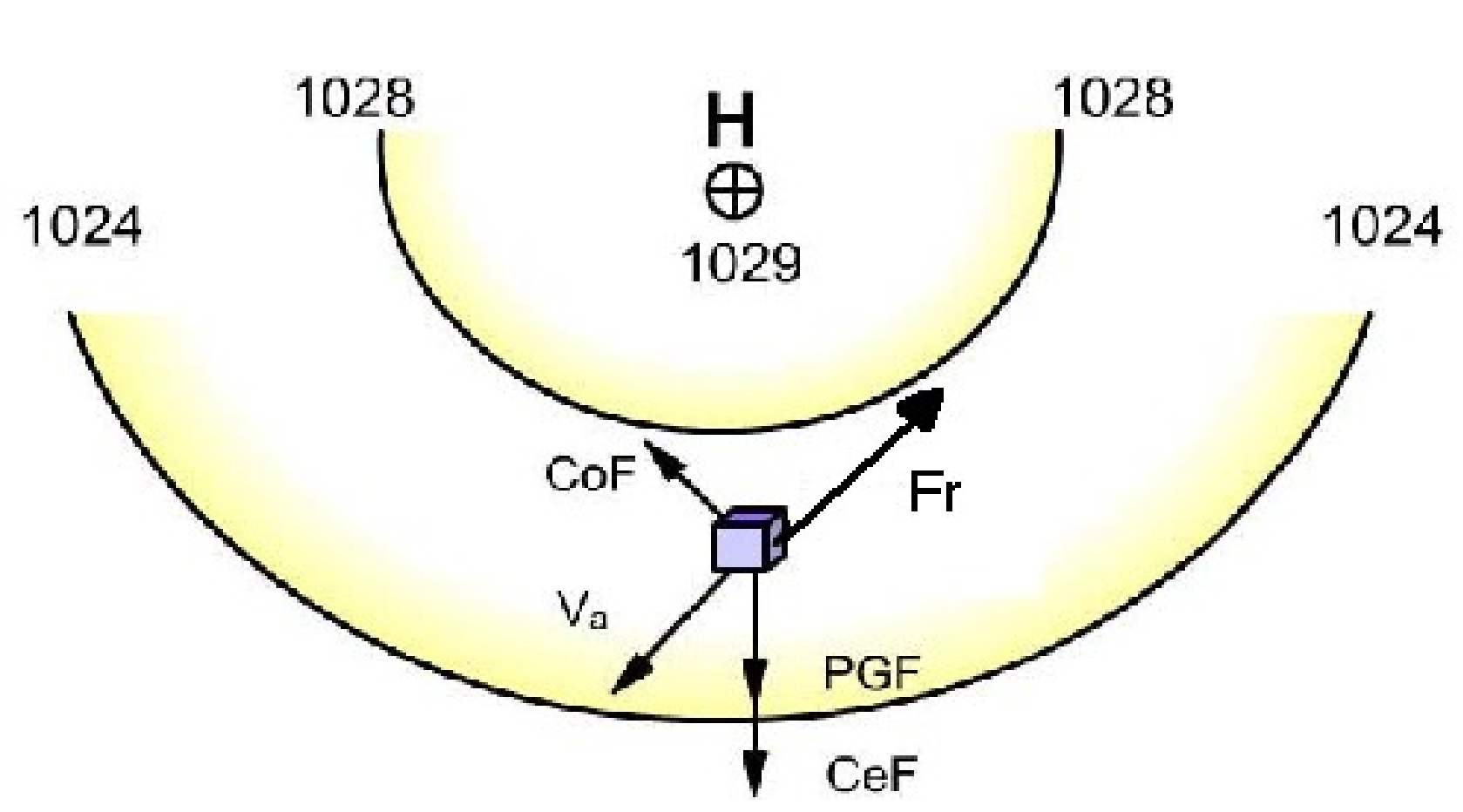
Effects of friction – A new balance is established with flow across the isobars toward lower pressure.



Effects of friction on V_c

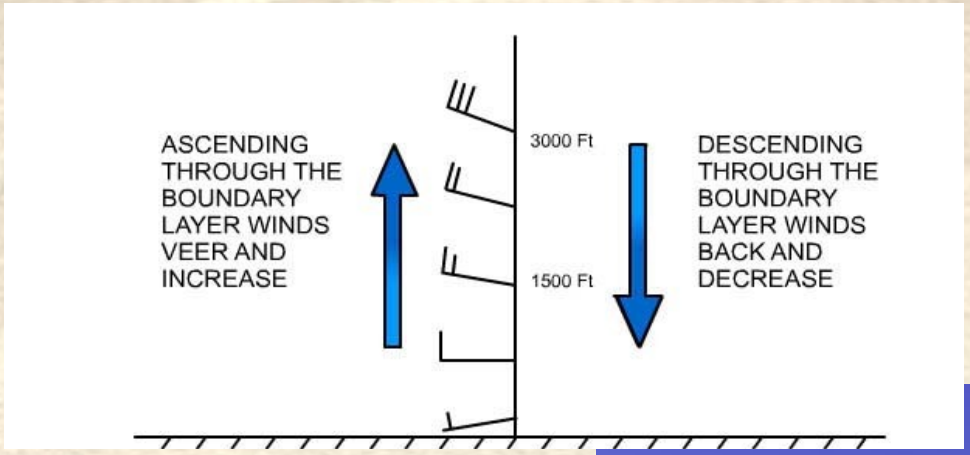


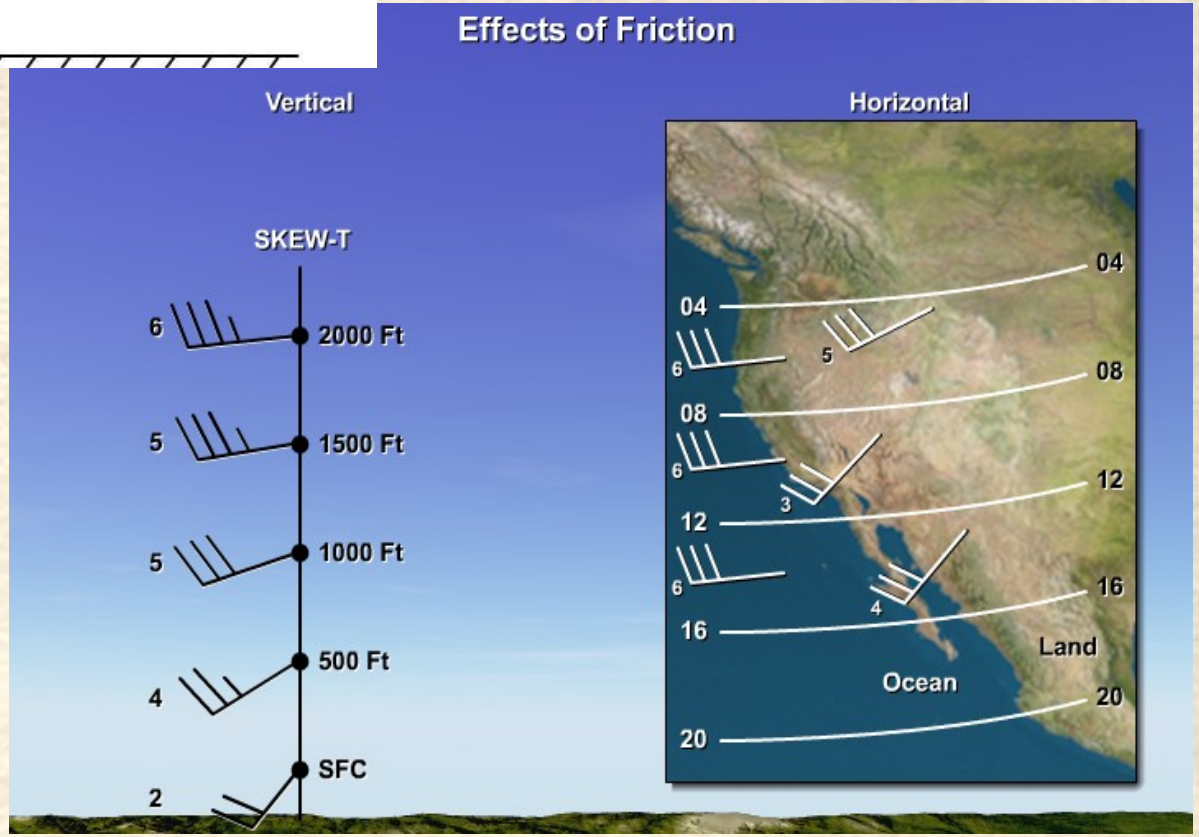
Effects of friction on V_a



Frictional Forces (Fr)

- Frictional effects in the vertical
  - Planetary Boundary Layer (PBL)
    - Also referred to as friction layer
    - That part of atmosphere where Earth's surface has appreciable effect on air motion.
    - On average – surface to roughly 1000 m to 3000 ft above ground level (AGL).
  - Gradient Level – Top of the boundary layer

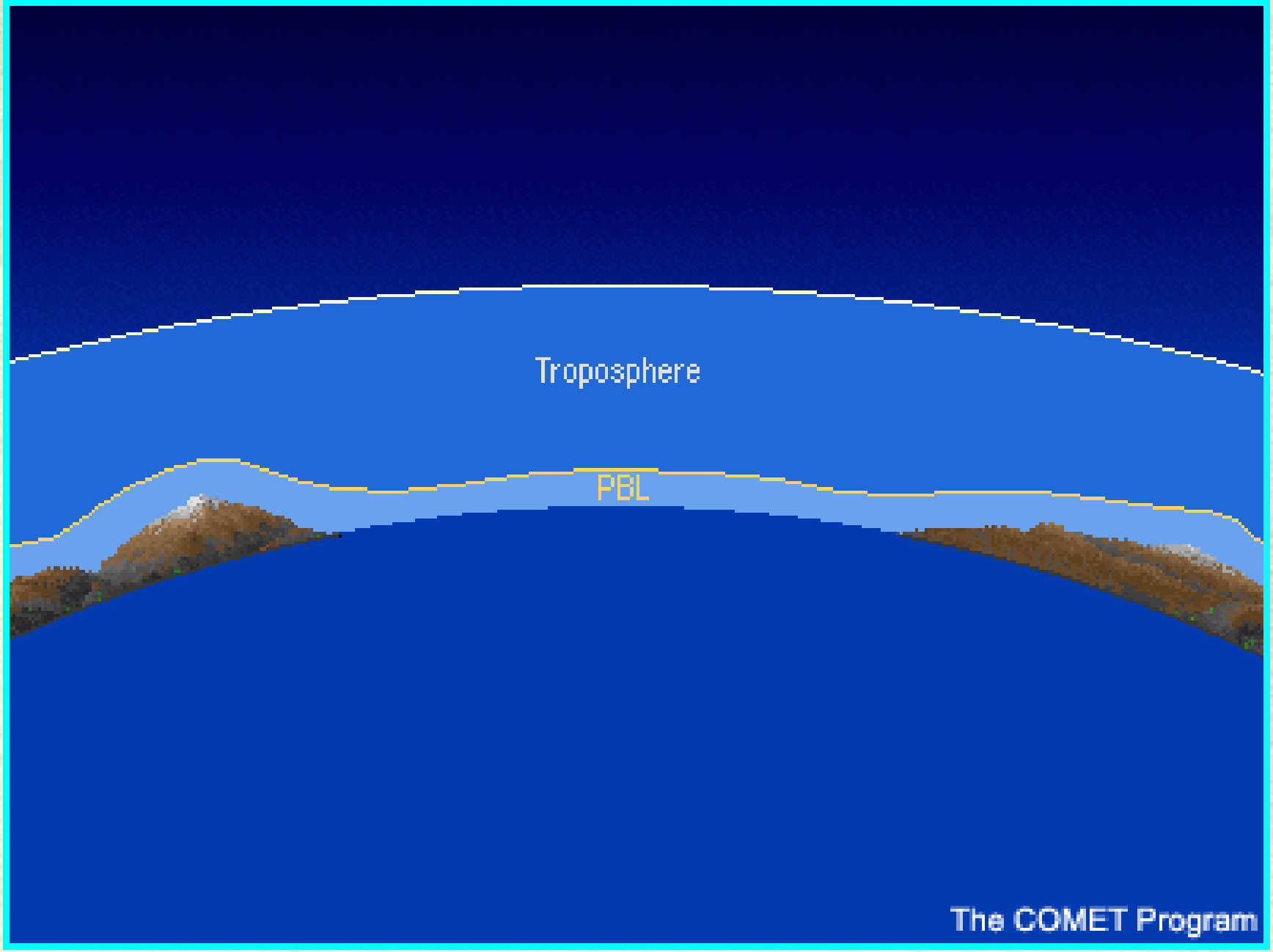

ASCENDING THROUGH THE BOUNDARY LAYER WINDS VEER AND INCREASE
3000 Ft
1500 Ft
DESCENDING THROUGH THE BOUNDARY LAYER WINDS BACK AND DECREASE


Effects of Friction
Vertical
SKEW-T
6
2000 Ft
5
1500 Ft
5
1000 Ft
500 Ft
4
SFC
2
Horizontal
04
04
6
5
08
08
6
3
12
12
6
4
16
16
Land
Ocean
20
20

Frictional Forces (Fr)

- The depth of the PBL depends critically on terrain, and wind temperature profiles near the surface. The planetary boundary (friction) layer height varies with:

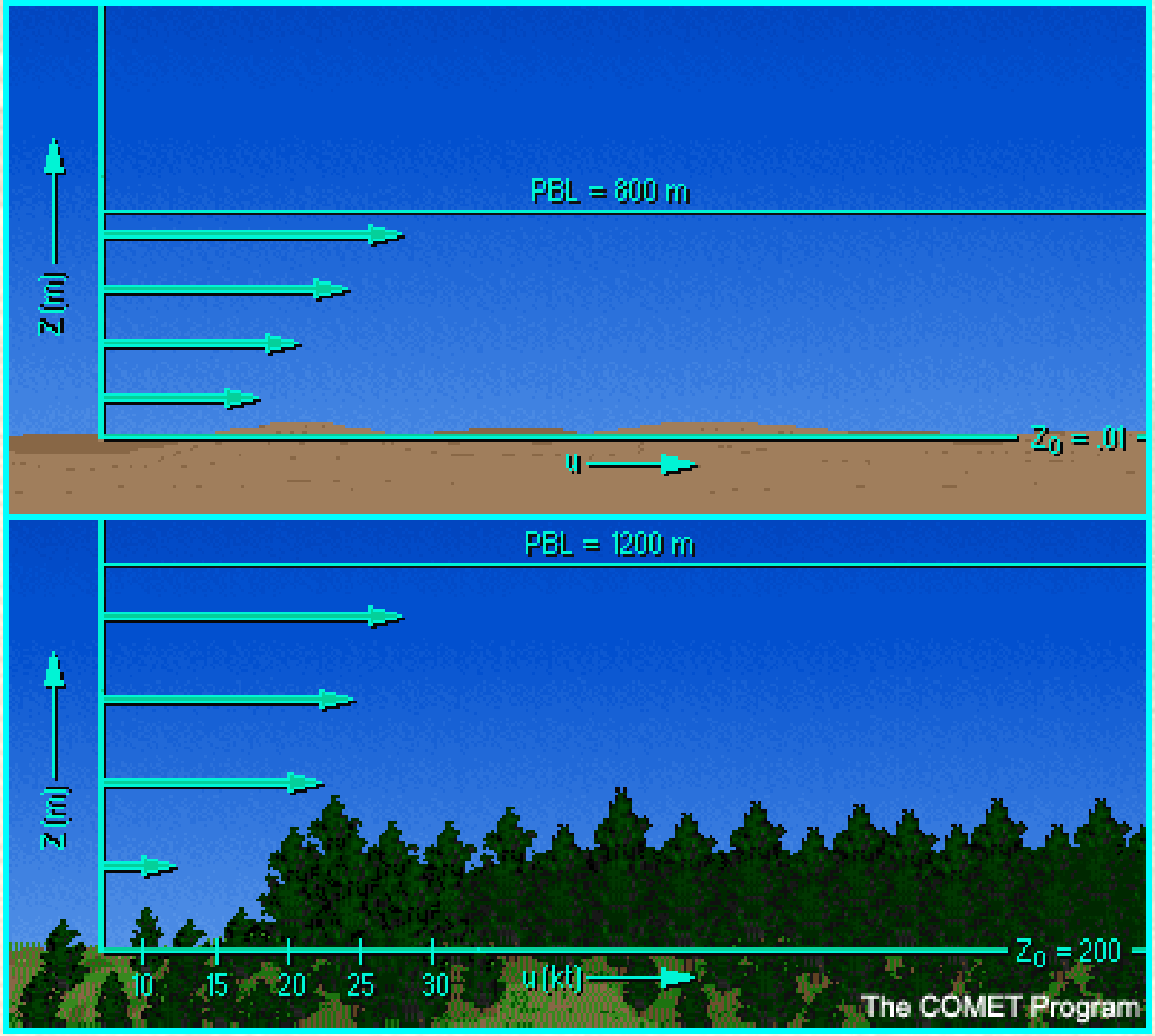
  - Terrain – Rough terrain
    - Greater the mechanical turbulence
    - Deeper the boundary layer


Troposphere
PBL
The COMET Program

Frictional Forces (Fr)

- Wind – Increased vertical speed shear or increase of wind speed with height
  - Greater the mechanical turbulence
  - Deeper the boundary layer

- Stability – less stable atmosphere
  - Stronger UVM and mixing of atmosphere
  - Deeper the boundary layer

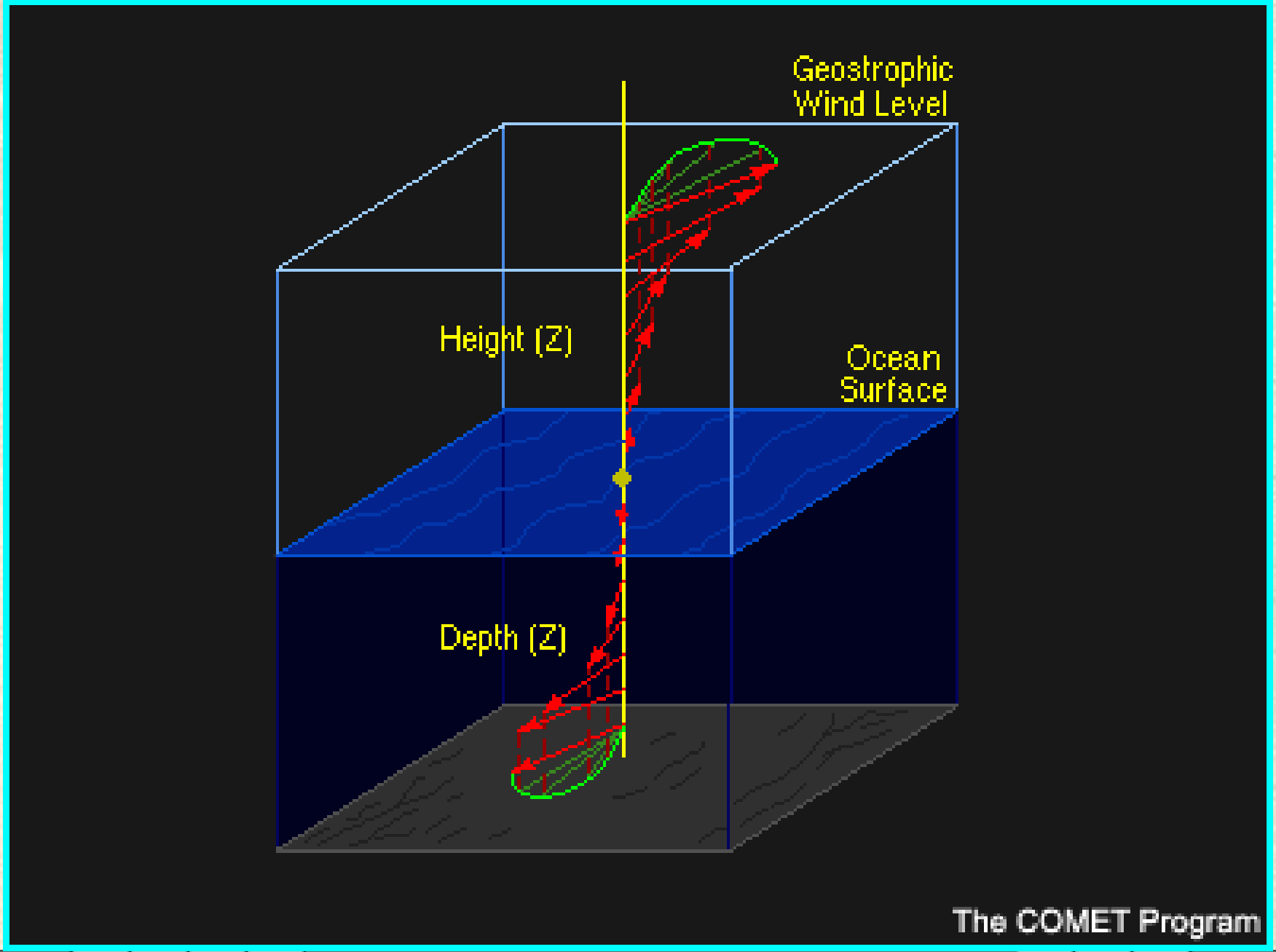

PBL = 800 m
Z (m)
Z_0 = .01
u
PBL = 1200 m
Z (m)
Z_0 = 200
10
15
20
25
30
u (kt)
The COMET Program

Frictional Forces (Fr)

- Intense surface heating
  - Result in greater mixing
  - Deeper boundary layer
- Surface cooling
  - Result in less mixing
  - More shallow boundary layer over land

Frictional Forces (Fr)

- The Ekman Spiral – The change of frictional effects on the wind with altitude
  - Ascending through the boundary layer
    - Results in decreased friction
    - Winds increase and veer
    - Winds are essentially in gradient balance at the top of PBL


Geostrophic
Wind Level
Height (Z)
Ocean
Surface
Depth (Z)
The COMET Program

Frictional Forces (Fr)

- Descending through the boundary layer
  - Winds are essentially in gradient balance at top of PBL
  - Descent toward the surface results in increased friction
  - Winds decrease and back

- APPLICATION: ST: Review Exercise 2
- EVALUATION: Informal: Appraisal

  Formal: Written Test